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TECHNICAL REPORT
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DESIGN OF THE COMPARTMENTED MEAL TRAY FOR SIMULTANEOUS THERMOPROCESSING OF FOODS

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Computer simulations were used to design a three-compartment meal tray for simultaneously thermal processing three different foods. Based on computer predictions, several prototype trays were made and their performance was verified with experiments. Among the prototype trays was the "one-tray design," which was flexible enough to accommodate all the menu combinations provided by the U.S. Army Natick Research, Development and Engineering Center (Natick). This design uses paper napkin material to insulate the heat-sensitive food during retorting.

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PREFACE

In May of 1989, the U.S. Army Natick Research Development and Engineering Center (Natick) awarded a three-phase research and development contract to Rutgers University, Food Science Department, Contract Number DAAK60-89-C-1028. During the period 31 May 1989 to 31 May 1991, four primary investigators and several graduate students worked on the project, which was to design and fabricate a compartmented tray for simultaneous thermoprocessing of foods. This report is a result of their work.

Natick Project Officer responsible for monitoring this contract was Ms. Lauren Oleksyk of the Subsistence Protection Branch (SPB), Food Engineering Directorate (FED). The required technical support was provided by Mr. Jay Jones, also of SPB, FED.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

ABBREVIATIONS, ACRONYMS AND SYMBOLS

i.e.	that is
BBQ	barbecue
EVOH	ethylene vinyl alcohol copolymer
FDA	Food and Drug Administration
GE	General Electric
Natick	U.S. Army Natick Research, Development and Engineering Center
PP	polypropylene
PPO	polyphynelene oxide
PS	polystyrene
PY	polyester
TSA	tryptic-soy agar
^oC	degrees Celsius
cm	centimeter
F_o	sterilization value
g	grams
min	minute
ml	milliliter
mm	millimeter
psig	pounds per square inch (gauge)

SUMMARY

Concepts were developed for the design of a three-compartment meal tray that could be used for simultaneously thermal processing three different foods. Based on these concepts, computer programs were written to calculate the temperature history and the F_o value of foods. Computer simulations were conducted to obtain several optimum tray dimensions. Subsequently, prototype trays based on these optimum tray dimensions were made, and their performance was successfully verified with experiments.

Among the prototypes was the "one-tray design," which was flexible enough to accommodate all the menu combinations provided by Natick. Without this design, different trays would be necessary for different menus. The computer simulations indicate, at least theoretically, that this one-tray design is capable of being used to simultaneously thermoprocess three different foods. Specifically, the one-tray design uses an outer tray for menus consisting of only low-acid foods, or the same outer tray with an insulated inner tray for menus consisting of both high- and low-acid foods.

A unique feature of this one-tray design is that it uses multilayered pulped cellulose material to insulate the inner tray. The multilayered pulped cellulose serves not only as an insulator to protect the heat-sensitive food inside the inner tray during retorting, but also as a napkin during meal time for the soldier. The napkin also has the advantage of being an environmentally-friendly, degradable product.

DESIGN OF THE COMPARTMENTED MEAL TRAY FOR SIMULTANEOUS THERMOPROCESSING OF FOODS

INTRODUCTION

The objective of this project was to design and fabricate a polymeric, compartmented tray with a hermetically sealable lid that can be used to simultaneously heat-process an entire meal consisting of an entree, starch, and dessert, such that each food component receives the acceptable sterilization value (F_o). Since the food components can have different heat sensitivities, they must be selectively heat-processed. To achieve this objective, two methods were tested: varying the initial temperatures of the individual foods at the start of the retort, and controlling the heat conduction process. Although the first method required a shorter process time and allowed more economical package designs, previous data (with chili con carne, white rice and peach slices) indicated that simultaneous heat processing of the meal components was not feasible by adjusting the initial temperatures of the meal components alone.[1] This conclusion was generally true for other combinations consisting of both high- and low-acid components. The second method was implemented by applying a layer of insulation on the outside surfaces of the component which had the least process lethality. Since previous data showed that this method was effective, it was applied in this project to a wide combination of food items. The prototype packages were designed according to

the specifications in the solicitation document and FDA regulations.

This project was implemented in three phases over a period of two years. Phase I efforts covered four areas: development of computer programs, package design, verification of computer predictions with experimental data and computer simulations. Phase II involved working closely with packaging equipment manufacturers to design and manufacture initial prototype trays and molds. Prototype trays were tested and a one-tray design was finalized. Phase III consisted of the fabrication of 200 compartmented trays of the final design.

This report is divided into three individual technical reports, one for each phase of the contract.

PHASE I

DESIGN OF A COMPARTMENTED TRAY

INTRODUCTION

The objective of Phase I was to design a compartmented, thermostabilized polymeric meal tray, with a hermetically sealable lid, which can be used to simultaneously thermal process three different foods. A major task in accomplishing this objective was to develop a heat-transfer model and conduct experiments to test its validity. Phase I activities included the development of computer programs to calculate the temperature history (heating and cooling profiles) and lethality values (F_o) of foods inside a tray during the retort process; incorporation of an optimization subroutine into the program for estimating the convective heat transfer coefficients; estimation of thermal and physical properties of foods; verification of theoretical predictions with experiments; development of several tray design concepts; conduction of computer simulations to optimize the tray dimensions; and recommendation of several tray designs.

TECHNICAL APPROACH

A. COMPUTER MODELING

A computer program based on a model describing the heat transfer in an infinite slab was developed. The partial differential equation of the model

was solved with an explicit finite difference method. The model had the advantage that its boundary conditions could be modified easily. Early in Phase I, the computer program, based on this model, was used to simulate heat transfer in plastic containers with only one compartment. The model was later refined to describe the three-dimensional heating and cooling profiles of foods inside a compartmented tray during the retort process. This was done by incorporating other necessary features into the model, such as the geometry of the tray and the thickness of insulation material, for predicting heat transfer in trays with three compartments.

1. Three-Dimensional Heat Transfer:

The model was extended from one-dimensional to three-dimensional, which more realistically described the unsteady state heat-transfer process of food in a brick-shaped package. Two complementary computer programs were developed; one based on an analytical solution and the other based on a numerical solution. The model that uses the analytical solution is based on Newman's multiplication rule of one-dimensional, unsteady state, heat conduction equation. This solution assumes that the overall heat transfer coefficient is the same for all sides of the tray, that the tray and lid have the same thickness if they are made of the same material, and that the temperature profile is symmetrical along the three axes. It is noteworthy that the latter consequence is desirable because it means the foods inside the tray are thermally processed more uniformly. Appendix A contains a description of the program and related codes. The analytical program, originally written in BASIC, was later converted into FORTRAN codes for faster compilation and

execution. The overall flow diagram for the simulation model is shown in Figure 1, and the flow diagram for estimating the process time and insulation thickness is shown in Figure 2. Appendix B presents a sample output for predicting the process time and the insulation requirement for thermally processing a three-compartment tray containing beef, rice and pears.

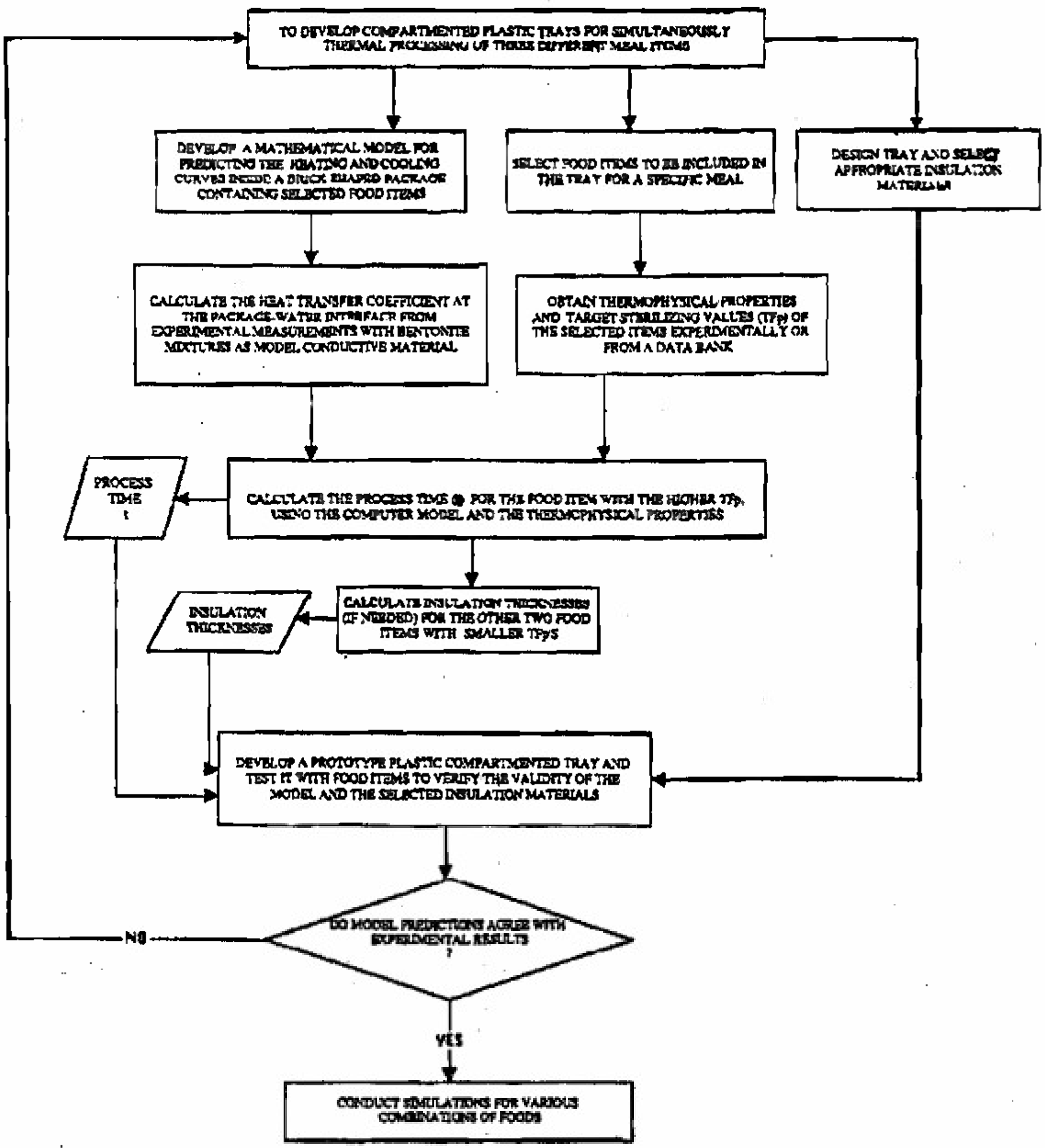

Figure 1. Flow Diagram for Computer Modeling and Simulation

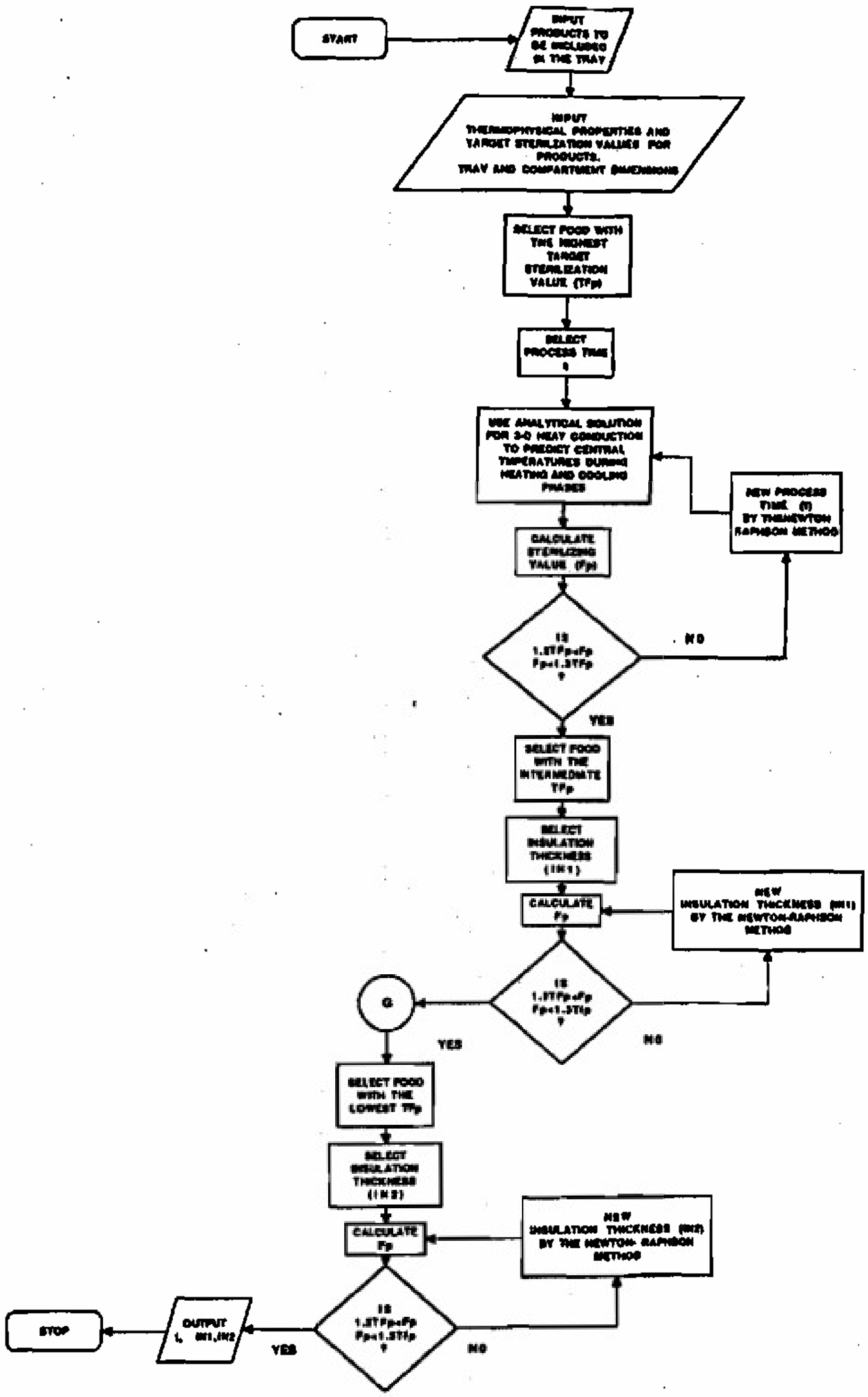

Figure 2. Estimation of Proper Process Time and Insulation Thickness for Compartmented Polymeric Tray

The complementary program, written in FORTRAN, was also developed to provide a numerical solution for the same problem using the explicit finite difference method. With this program, the tray and the lid were not limited to having the same thickness, and the output of the program could be used to check against that of the first computer program for consistency. However, this program solution required longer computation time than the first program. Results from both the analytical and numerical programs were shown to have good correlation.

2. Optimization Subroutine:

The optimization subroutine estimated the overall heat transfer coefficient, U, which was an important parameter in characterizing the tray geometry and the retort environment. The optimization technique was based on minimizing the sums of squares error (Figure 3).

B. THERMOPHYSICAL PROPERTIES DATA

Thermophysical properties, such as specific heat capacity, thermal conductivity, and thermal diffusivity, were estimated with software developed by European Cooperation in Scientific and Technical Research (COST), and were based on water, carbohydrate, protein and lipid contents of a given food. A series of experiments were also conducted to measure the actual specific heat capacity, thermal conductivity and thermal diffusivity of foods supplied by Natick. Preliminary data suggested that the experimental values for most of the foods agree within 10% of the theoretical values calculated by the COST program. Therefore, before all of the experimental values were available, this program was used to calculate the thermal properties of foods used in the tray designs described in Section F. Calculated properties are listed in Table 1.

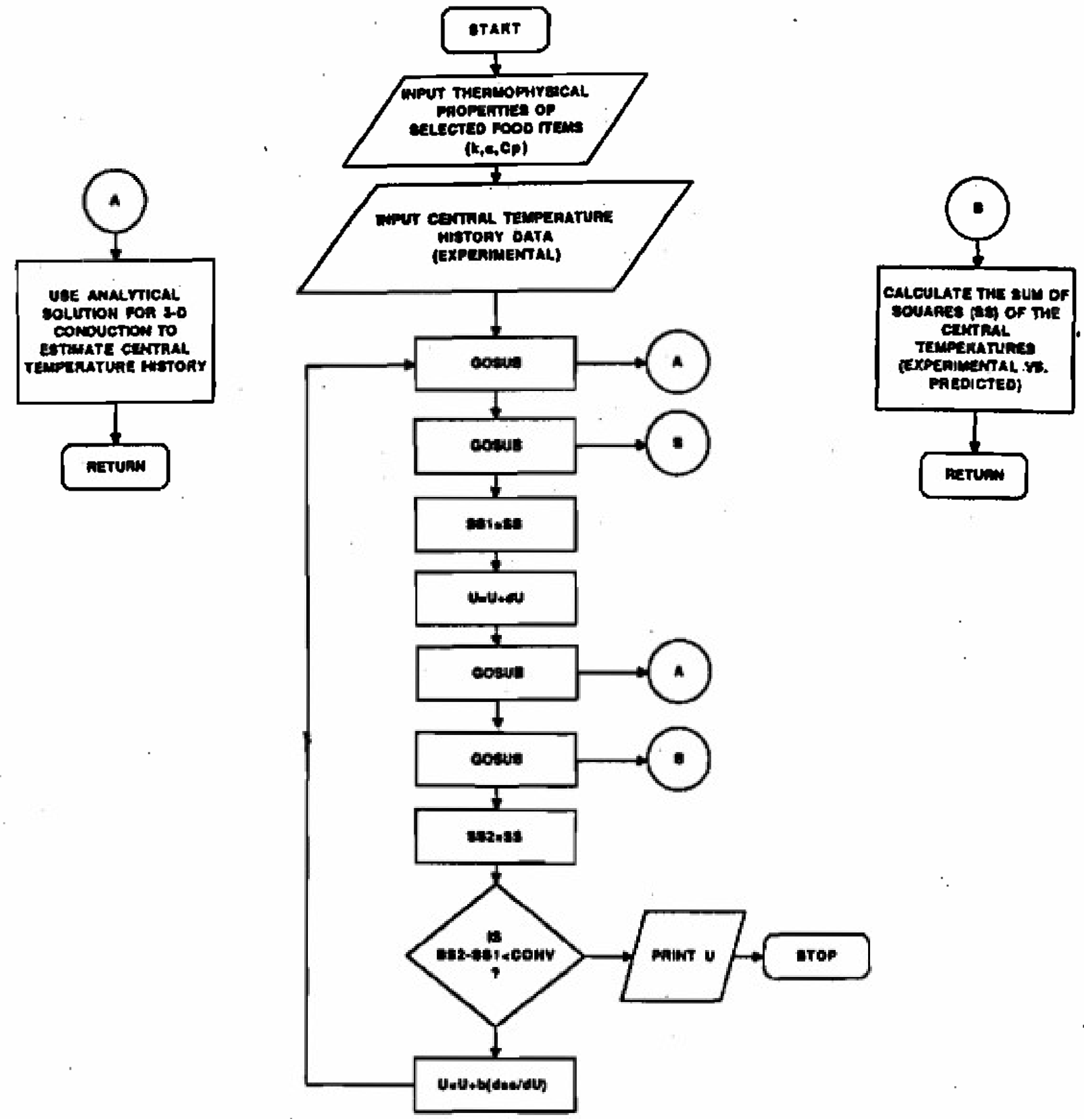

Figure 3. Estimation of the Overall Heat Transfer Coefficient, U (cont.)

C. EXPERIMENTAL VERIFICATION

1. Equipment Purchased and Installed:

An Omega White Box high resolution data acquisition system with an NEC 12 MHz 286 computer was purchased and installed for storing and manipulating

experimental data obtained from a still retort. For computer simulations, an HDS graphic terminal was connected via a modem to the VAX mainframe computer at Rutgers University.

Table 1. Thermal Properties Calculated from COST Program

Item	Composition (%)					Thermal properties	
	Water	Protein	Fat	Ash	Carbohydrate	k	α
Pork	63.28	16.57	11.14	1.43	7.59	0.5339	1.521×10^{-7}
Rice	64.99	2.52	5.04	0.92	26.44	0.5622	1.591×10^{-7}
Apple	72.81	0.27	0.89	0.24	25.71	0.6004	1.622×10^{-7}
Chili	65.38	13.13	13.60	1.04	6.86	0.5381	1.533×10^{-7}
Peach	81.13	0.49	0.13	0.17	18.00	0.6295	1.635×10^{-7}
Beef	73.56	11.40	5.59	1.57	7.89	0.5853	1.573×10^{-7}
Fruit	80.88	0.39	0.21	0.15	18.28	0.6285	1.635×10^{-7}
Chocolate	54.15	1.50	1.96	1.07	41.23	0.5291	1.580×10^{-7}
Hamburger	69.13	17.57	11.47	1.71	0.13	0.5534	1.531×10^{-7}
Carrot	92.63	0.86	0.14	0.97	5.32	0.6650	1.648×10^{-7}

k = thermal conductivity [J/m sec °K]

α = thermal diffusivity [m^2/sec]

2. Preliminary Experiments and Results:

a. Temperature profiles:

Two sizes of plastic containers, with inside dimensions of 30 by 70 by 118 mm and 26 by 92 by 136 mm, were provided by Natick for preliminary experiments. To measure the temperature profiles, thermocouples were inserted at the thermal center of each container as well as at two other nodal points. The containers were then filled with a 10% bentonite-water dispersion and heat sealed with a trilaminate material containing aluminum foil. A bentonite-water system was chosen as a food model because of its good chemical stability, low cost and versatility in a wide range of food applications.[2] Four containers

(two of each size described above) were placed inside the still retort operating with hot water at 121°C. After the containers were processed for one hour at 121°C and 40 psig, cold water (25°C) was introduced into the retort to complete the process cycle. As an example of the results obtained, the heating curve for a 30 by 70 by 118 mm container (Figure 4) shows that the center temperature (Curve 2) continued to rise for three more minutes, even after the cooling phase began (Curve 1). This suggested that the heat inside the container was transferred mainly by conduction. Also shown in Figure 4 are computer predictions of the heating curves with various overall heat transfer coefficients, U (Curves 3, 4 and 5). By trial-and-error, it was discovered that the prediction with U=50 W/m^2K yielded the best result (Curve 5). Thus, with proper selection of U values, the computer program can accurately predict the behavior of heating curves during the retort process.

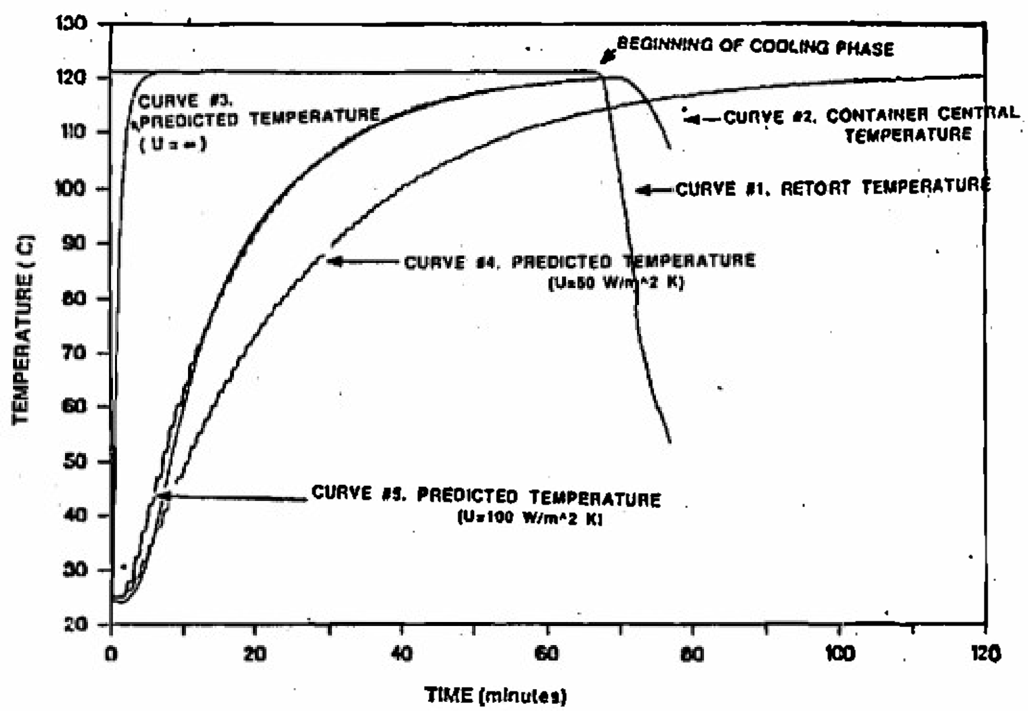

Figure 4. Experimental and Predicted Heating Curves (Bentonite)

b. Heat penetration rate:

The heat penetration rate through a container during the retort process depended on the size of the container and the overall heat coefficient (U) of the container. The heat coefficient (U) also depended on the material of the container, the retort conditions, and the amount of head space in the container. An important task in the experimentation was to estimate the overall heat transfer coefficient (U) from the heating and cooling curves obtained from retort experiments. A retort manufactured by STOCK was operated in the still mode at a temperature of 121.1^{o}C, with a heating time of 60 minutes and cooling time of 20 minutes, respectively. The containers used were provided by Natick and had dimensions of approximately 120 by 80 by 35 mm. The containers were filled with 10% bentonite suspension in water (thermal conductivity, $k=0.637$ W/m^{o}K and thermal diffusivity, $\alpha=1.587e-7$ m^2/s) to simulate food, and then covered with plastic lids of the same material and thickness of the container to provide uniform heat resistance for all the surfaces. Five thermocouples were placed inside the container, at locations of 1.15, 1.55, 1.75 (geometric center), 1.95, and 2.35 mm, to monitor the temperature profile of the container during both the heating and cooling phases. The thermocouples were held in place by a Teflon insert adhered to the walls of the container by silicon adhesive.

With the aid of the computer program, the overall heat transfer coefficient was obtained from the experimental heating and cooling curves. The overall heat transfer coefficient was fed back to the program to generate the theoretical predictions. As presented in Figure 5, there was good correlation between the experimental data and the predicted data.

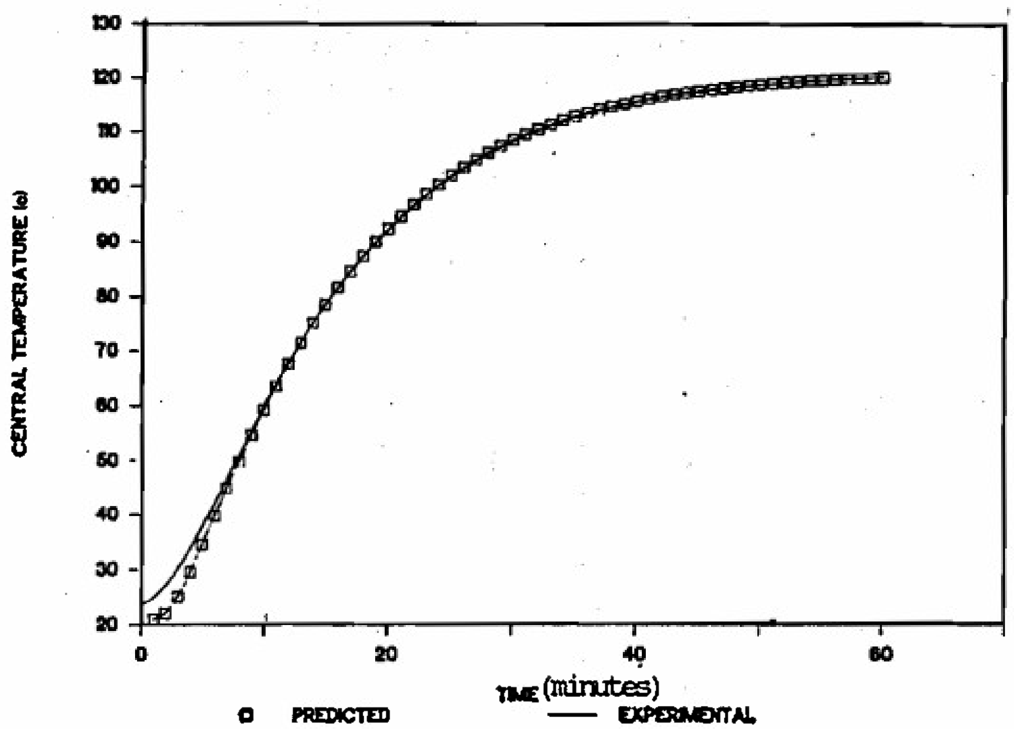

Figure 5. Experimental Versus Predicted Data

3. Effect of Head Space:

The amount of head space in the tray was an important design consideration because it can greatly affect the heat penetration rate during the retort process. To quantify the influence of the head space, a series of experiments were conducted where the head space inside a bentonite-filled container was carefully adjusted to a specified height. The container was then immersed in warm water (55^{O}C) and the temperature at five nodes was monitored over time by a data acquisition system. The head spaces used in these experiments had the heights of 0, 0.05 and 2.00 mm. To compare the data from different heights of head space, the temperatures at each node were averaged over a 15-20 minute interval. Figure 6 shows these average temperatures as functions of the height of the head space and the location of the node. Also shown are the true thermal centers for each head space (located at the minimum of the second order

polynomial regression line which connect the average nodal temperatures) along with the location of the geometric center. It can be seen that a small change in head space could change the location of the thermal center significantly. This information was incorporated in the final design of the compartmented tray.

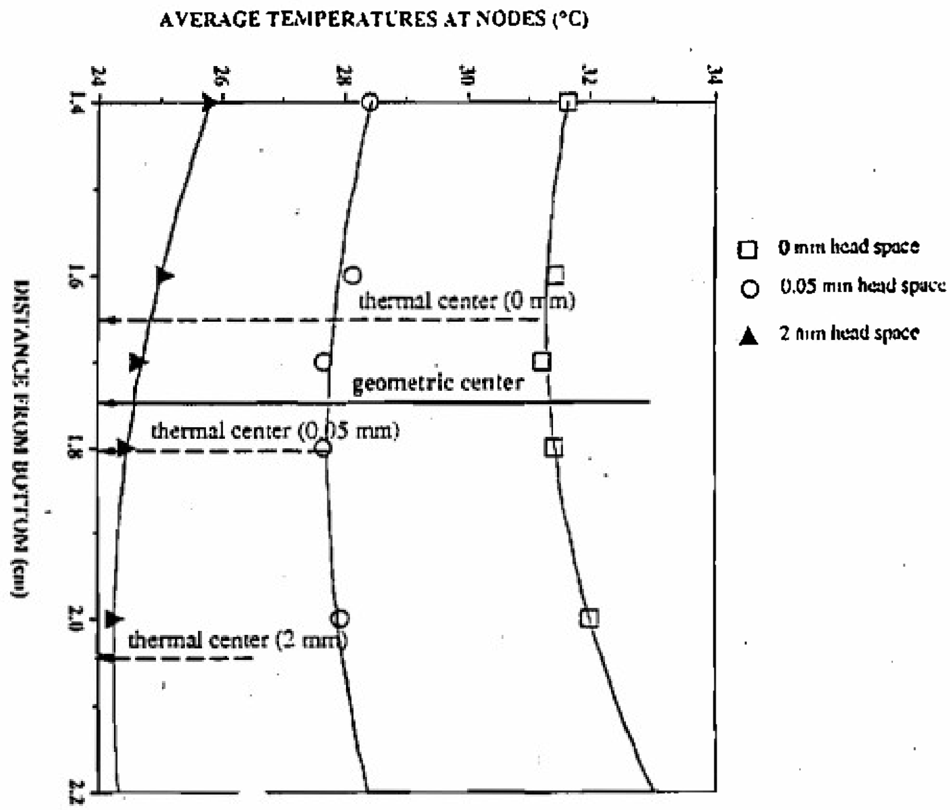

Figure 6. Locations of Thermal Center Versus Head Space

D. TRAY DESIGN CONCEPTS AND INSULATION MATERIALS

The existing designs of commercial compartmented trays, available in this country and in Europe, were reviewed. Insulation materials suitable for protecting heat-sensitive components in the thermostabilized meal trays were sought. Insulation materials were required to be FDA approved, able to endure the retort process and provide effective insulation. One potential insulation material that was identified included a heat-resistant, expanded

polyphynelene oxide (PPO)/styrene foam developed by General Electric (GE) Plastics. Different grades of expanded polystyrene and other FDA approved insulation materials were examined for performance at a later date.

The principles of enhanced conduction and insulation were explored in this phase to modify the heat processing of foods. Several tray design concepts for simultaneously processing different food items were developed and are outlined below.

1. Conduction:

For enhanced conduction, conducting fins may be used to shorten the processing time of heat-resistant foods. In this design, conductive fins are inserted into the compartment containing the food which requires the most heat, to enhance heat transfer (Figure 7). The fins must have good heat conductivity and be compatible with the food in the tray compartment.

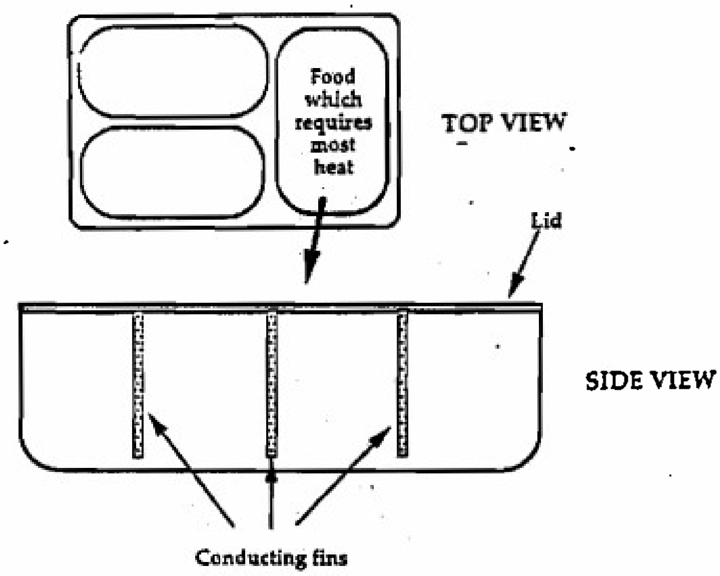

Figure 7. Heat-Transfer Enhancement With Conductive Fins

2. Insulation:

For insulation, three design concepts have been developed to avoid overprocessing of acid foods:

a. Insulation with processing rack: A specially designed processing rack may also be used to selectively insulate the compartment containing the heat sensitive food (Figure 8). The advantage of this concept is that the tray does not require the insertion of extra insulation or conductive elements. The disadvantage is the capital cost for producing the processing racks. Also, since the processing rack concept deviated from the original contract proposal, it was considered only as a potential alternative which would require further investigation.

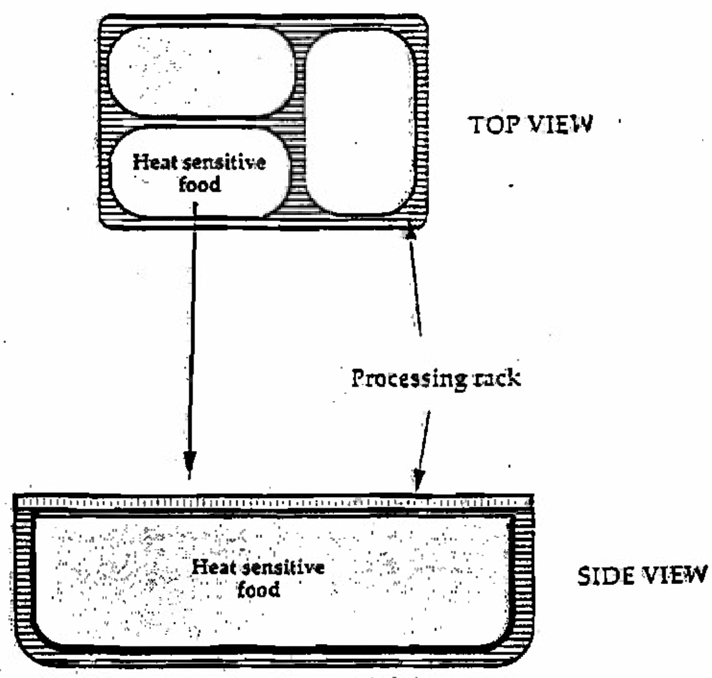

Figure 8. Insulation With Processing Rack

The other two design concepts apply an insulation feature directly to the tray design. There are two trays involved in this concept, a compartmented outer tray and an inner tray, as shown in Figure 9. The compartment containing the more heat-sensitive food is thermally protected by an insulation insert and an air space between the inner and outer tray. The thickness of the insulation and air space may be estimated by the computer simulation model. The two designs based on this concept are outlined below.

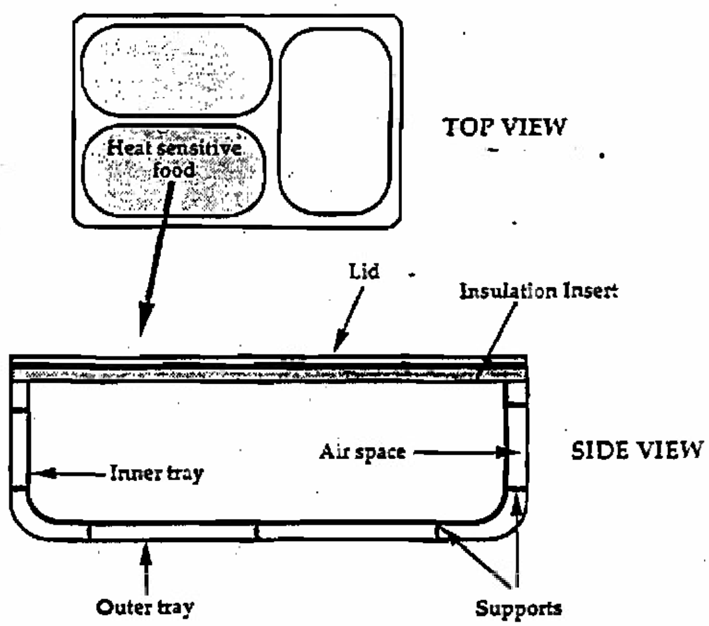

Figure 9. Insulation Insert With Inner Tray

b. Insulation with heat-resistant foam: The outer tray is thermoformed into three compartments; one for the entree, one for the starch, and one for a foamed inner tray which contains the heat-sensitive dessert (Figure 10). The outer tray is made of a multilayer coextrusion of structural polypropylene (PP) and high-barrier ethylene vinyl alcohol (EVOH) polymers.

The inner tray is made of a foam material which is used to provide heat resistance to the sensitive food contained in the tray during retorting. An advantage of using an inner tray is that it offers the soldiers the choice of removing the dessert from the outer tray before reheating. It is necessary to seal the inner tray, as well as the outer tray, with lids. Because the lid for the inner tray does not provide sufficient heat resistance, a piece of foam may be needed to place on top of the lid to provide additional insulation.

c. Insulation with napkin material: The outer tray is thermoformed in the same shape and with the same material as described in paragraph b above. However, instead of using a foam material to provide the needed insulation, this design incorporates a paper napkin material which is used to wrap around the inner

tray (Figure 10). The napkin is an inexpensive, food compatible, insulation material which also provides the soldier with convenience at meal time, and is environmentally-friendly because of its degradable nature. Since it is already protected by the outer tray, the inner tray may be made of less expensive packaging material such as polypropylene. No additional insert is needed to place on top of the inner tray because the entire tray is already protected by the napkin. The use of the napkin seems to provide the best features among the design concepts considered. Note in the designs described in paragraphs b and c that only the compartment which contains the dessert is heat insulated. To reconcile the differences in thermal properties between the other two foods (entree and starch) in the other two compartments, the dimensions of the compartments were used as a design variable to avoid over- or under-processing.

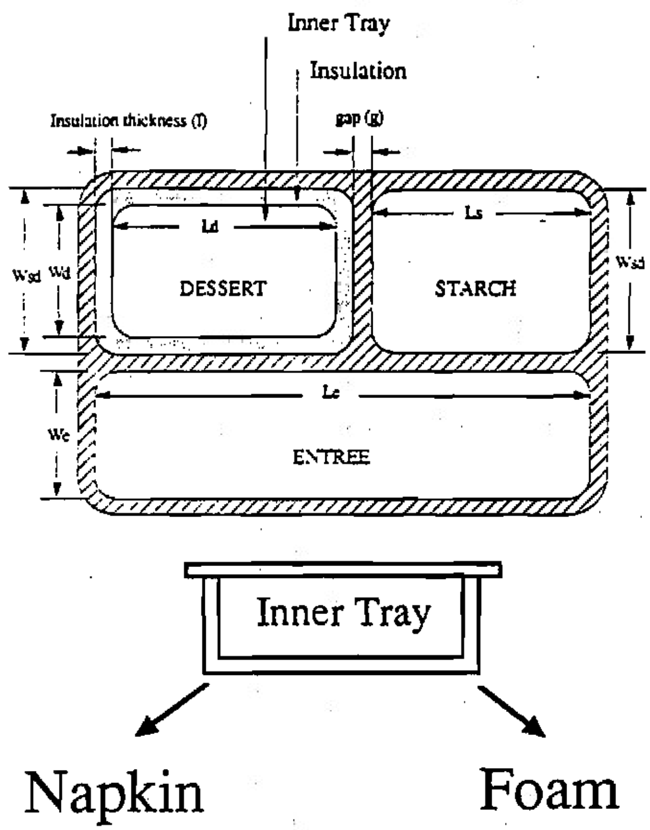

Figure 10. Insulation Methods for Inner Tray

E. OPTIMIZATION OF TRAY DESIGNS

The tray design which utilizes heat-resistant foam (to insulate the dessert compartment) was optimized using the computer programs along with the relationships and constraints listed in Table 2.

Table 2. Tray Design Constraints

Design variables:
- Insulation thickness (I)
- Height of the outer tray (H)
- Width of starch compartment (W_{sd})

Design variables and related equations:
- Volume of entree compartment=326.0 ml
- Volume of starch compartment=226.8 ml
- Volume of dessert compartment=226.8 ml
- Gap between compartments (g)=0.8 cm
- Height of dessert tray (H_d)=H-2I
- Length of starch compartment (L_s=226.8/(HW_{sd})
- Width of dessert compartment (W_d)=W_{sd}-2I
- Length of dessert compartment (L_d)=226.8/($H_d W_d$)
- Length of entree compartment (L_e)=g+L_s+L_d+2I
- Width of entree compartment (W_e)=326.0/(L_eH)

Target sterilizing values:
- For low-acid food $F_p(121.1^oC)$=6.1, z value of 10^o
- For acid food $F_p(100^oC)$=3.1, z value of 10^oC

Constraints for design variables:
- 1 mm < I < 4 mm
- 2 cm < H < 4 cm
- 6 cm < W_{sd} < 12 cm

Constraints for dependent variables:
- 20 cm < L_e < 35 cm
- 2 cm < H_d < 4 cm
- 20 min < Heat processing time < 100 min
- 6.0 < F_{pe} < 8.0
- 6.0 < F_{ps} < 8.0
- 91.0^oC < Final temperature of acid dessert < 121.1^oC

*Objective function = Abs(F_{pe} - 6.1) + Abs(F_{ps} - 6.1) + Abs(F_{pd} - 3.1 for acid foods or 6.1 for low-acid foods)

*Nonlinear numerical optimization with complex method was used to minimize the objective function by searching the design variables.

F. RECOMMENDED TRAY DESIGNS

1. Menus Selected:

Tray designs were optimized for the menu combinations listed in Table 3.

Note that Menus 1, 3 and 8 contain high- and low-acid foods, and Menu 11 contains only low-acid foods.

Table 3. Selected Menu Combinations

Menu#	Entree	Starch	Dessert
1	Pork BBQ Sauce	Rice	Apple Dessert
3	Chili con Carne	Rice	Peach Slices
8	Beef Stew	Chocolate Pudding	Fruit Mix
11	Hamburgers	Rice	Carrot Slices

2. Tray Dimensions:

Listed in Tables 4 through 9 are the tray dimensions, sterilization values, insulation thicknesses and processing times obtained from computer simulations (with the optimization scheme) conducted on Menu numbers 1, 3, 8 and 11. Figures 11 through 16 show the corresponding, actual sizes of the compartments. The sterilization value calculated for the acid dessert was based on a lower temperature ($100^{o}C$) than temperatures used for the entree and the starch ($121.1^{o}C$).

a. Insulation with foam (Menu No. 1):

The foam is assumed to have the thermal conductivity of polystyrene, 0.0419 $W/m^{o}K$. Table 4 and Figure 11 describe the tray dimensions for Menu No. 1.

b. Insulation with napkin (Menu Nos. 1, 3 and 8):

The napkin is assumed to have the thermal conductivity of paper, 0.130 $W/m^{o}K$. Table 5 and Figure 12 describe the tray dimensions for Menu 1. Table 6 and Figure 13 describe the tray dimensions for Menu 3, and Table 7 and Figure 14 describe the tray dimensions for Menu 8.

Table 4. Tray Dimensions for MENU #1 (Insulated with Foam)

Contents: Pork BBQ sauce, rice, and apple dessert

Compartment Dimensions

22.36	x	5.85	x	2.49	cm	(for entree)
10.09	x	9.02	x	2.49	cm	(for starch)
11.26	x	8.81	x	2.29	cm	(for dessert)

Insulation thickness: 0.10 cm

Processing time: 33.0 minutes

F_p values:

F_{pe} = 6.95 (entree)
F_{ps} = 6.10 (starch)
F_{pd} = 3.09 (dessert) based on 100 °C

Final dessert temperature 100.1 °C

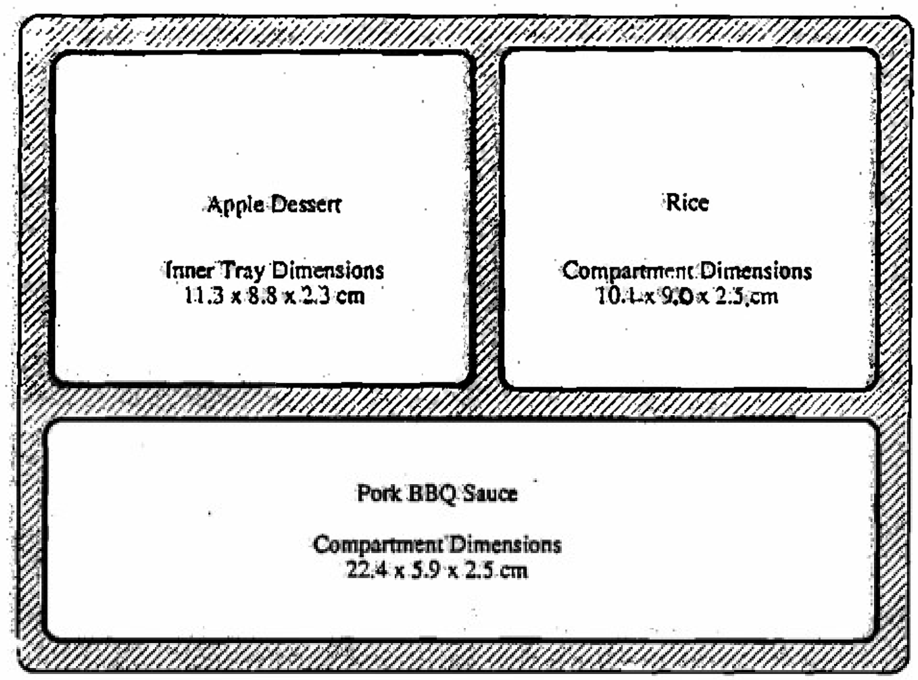

Figure 11. Tray Dimensions for MENU #1 - with Inner Foam Tray

Table 5. Tray Dimensions for MENU #1 (Insulated with Napkin)

Contents: Pork with BBQ sauce, rice, and apple dessert

Compartment Dimensions

21.05	x	5.25	x	2.95	cm	(for entree)
7.84	x	9.80	x	2.95	cm	(for starch)
11.63	x	9.02	x	2.16	cm	(for dessert)

Insulation thickness: 0.399 cm

Processing time: 39.3 minutes

F_p values:

F_{pe} = 7.9 (entree)
F_{ps} = 6.1 (starch)
F_{pd} = 7.6 (dessert) based on 100 °C

Final dessert temperature 100.1 °C

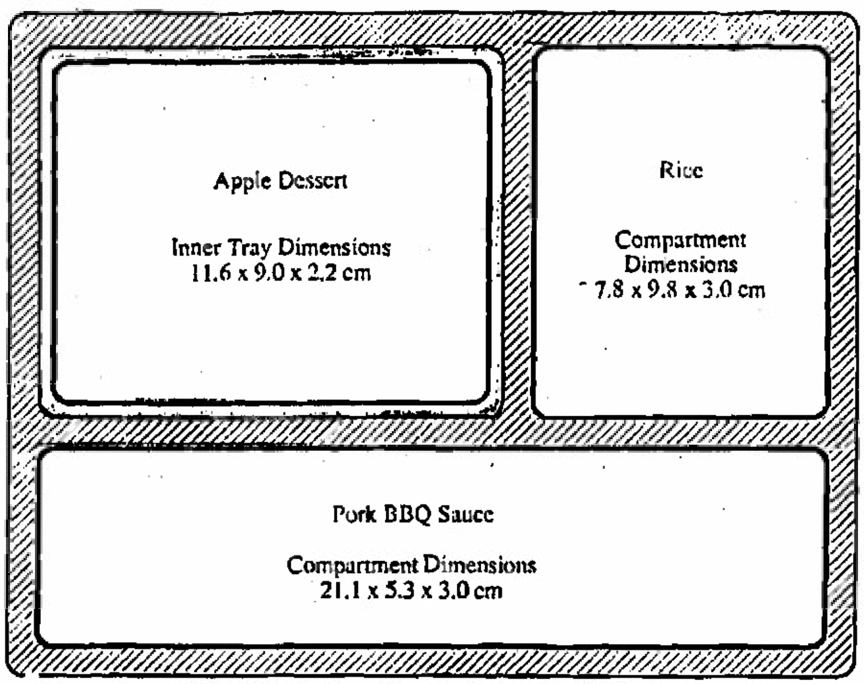

Figure 12. Tray Dimensions for MENU #1 - Insulated with Napkin

Table 6. Tray Dimensions for MENU #3 (Insulated with Napkin)

Contents: Chili, rice. peach slices

Compartment Dimensions

20.89	x	5.24	x	2.98	cm	(for entree)
7.83	x	9.72	x	2.98	cm	(for starch)
11.49	x	8.95	x	2.21	cm	(for dessert)

Insulation thickness: 0.386 cm

Processing time: 39.7 minutes

F_p values:

F_{pe} = 8.0 (entree)
F_{ps} = 6.1 (starch)
F_{pd} = 6.4 (dessert) based on 100 °C

Final dessert temperature 99.4 °C

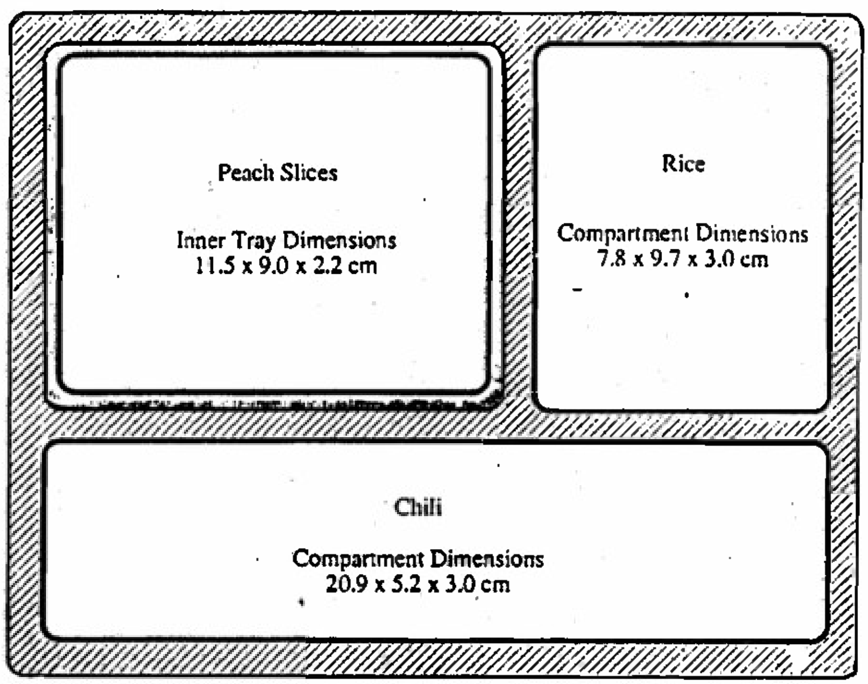

Figure 13. Tray Dimensions for MENU #3 - Insulated with Napkin

Table 7. Tray Dimensions for MENU #8 (Insulated with Napkin)

Contents: Beef stew, fruit mix, chocolate pudding

Compartment Dimensions						
	20.63	x 5.47	x	2.89	cm	(for entree)
	7.62	x 10.31	x	2.89	cm	(for starch)
	11.41	x 9.51	x	2.09	cm	(for dessert)

Insulation thickness: 0.399 cm

Processing time: 38.2 minutes

F_p values: F_{pe} = 7.7 (entree)
F_{ps} = 6.1 (starch)
F_{pd} = 5.5 (dessert) based on 100 °C

Final dessert temperature 98.9 °C

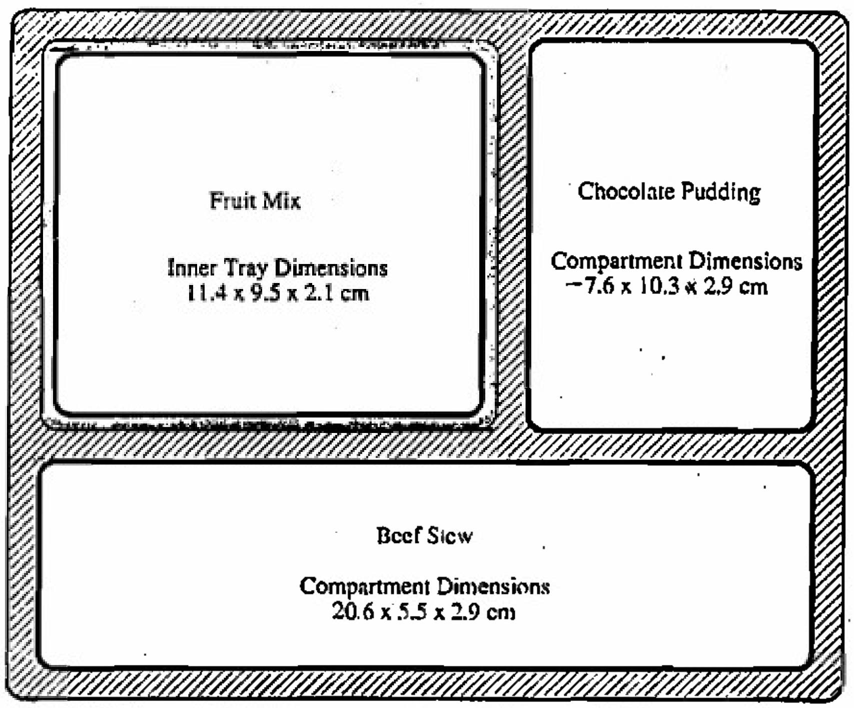

Figure 14. Tray Dimensions for MENU #8 - Insulated with Napkin

c. No insulation (Menu No. 11):

For a compartmented tray containing only low-acid foods with similar heat sensitivities, no insulation was required. Table 8 and Figure 15 describe the tray dimensions for Menu 11.

Table 8. Tray Dimensions for MENU #11 (Low-Acid Foods, No Insulation)

Contents: Hamburger, rice, carrot slices

Compartment Dimensions

20.98	x	6.45	x	2.41	cm	(for entree)
10.09	x	9.33	x	2.41	cm	(for starch)
10.09	x	9.33	x	2.41	cm	(for vegetable)

Insulation thickness: 0 cm

Processing time: 31.9 minutes

F_p values:
F_{pe} = 6.4 (entree)
F_{ps} = 6.2 (starch)
F_{pd} = 6.1 (vegetable) based on 131.1°C

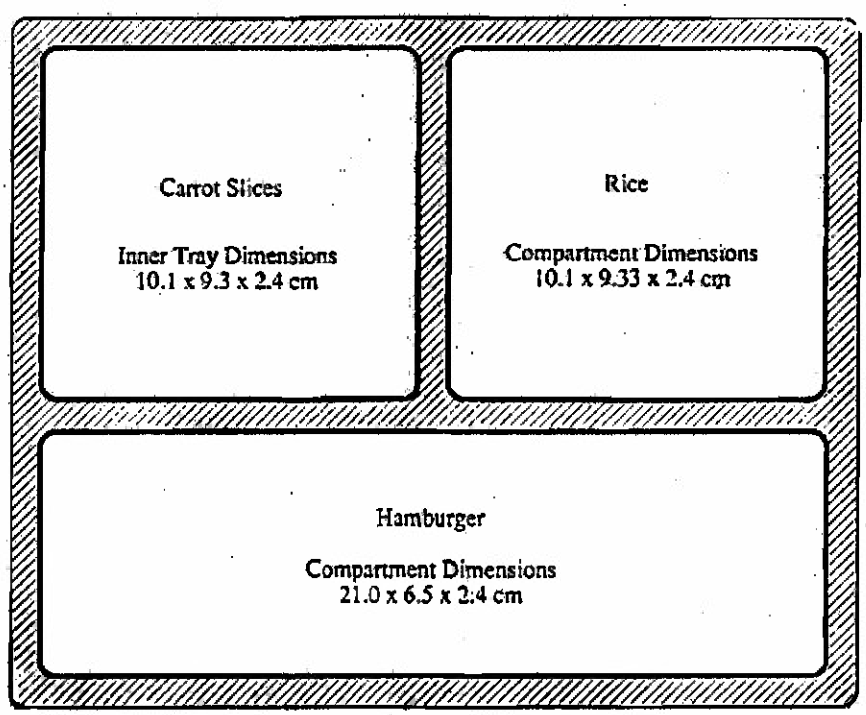

Figure 15. MENU #11 - All Low-Acid Foods (No Insulation)

DISCUSSION

Selective heating of the food components was achieved by designing the proper tray dimensions and selectively using insulation with an inner tray. The use of the inner tray and insulation was found to be necessary because changing the tray dimensions alone was not sufficient to achieve the desirable range of sterilization values for both high- and low-acid foods. For best results, a different tray was designed for each menu.

For combinations of high- and low-acid foods, the tray designs shown in Figures 11 through 14 show very similar dimensions. Therefore, it was determined possible to have one design (consisting of outer and inner trays) to accommodate several menus. For all low-acid foods, it was determined possible to use only an outer compartmented tray.

The compartment designed for the entree had a very slender dimension (Figures 11 through 15) which may create problems during filling of certain foods. To correct this problem, new computer simulations were conducted with a constraint imposed in the optimization scheme on the ratio of the width and length dimensions of the entree compartment (W_e/L_e). The ratio of W_e/L_e for Figures 11 through 15 was set at approximately 0.25. Table 9 and Figure 16 depict this tray for Menu 1 with the additional constraint of W_e/L_e=0.3.

A number of manufacturers, such as DuPont, Multivac, and Mahaffy and Harder were visited to discuss the tray design concepts identified above and the feasibility of manufacturing such trays. General Plastics also agreed to provide a PPO/PS foam tray material for testing, although it was not yet approved by FDA for food contact.

Table 9. Tray Dimensions for MENU #1

(Inner Tray Insulated with Napkin, W_e/L_e=0.3)

Contents: Pork BBQ sauce, rice, and apple dessert

Compartment Dimensions

20.00	x	6.00	x	2.72	cm	(for entree)
7.56	x	11.10	x	2.72	cm	(for starch)
10.93	x	10.33	x	2.01	cm	(for dessert)

Insulation thickness: 0.354 cm

Processing time: 36.0 minutes

F_p values:

F_{pe} = 6.6 (entree)

F_{ps} = 6.1 (starch)

F_{pd} = 9.7 (dessert) based on 100 °C

Final dessert temperature 101.5 °C

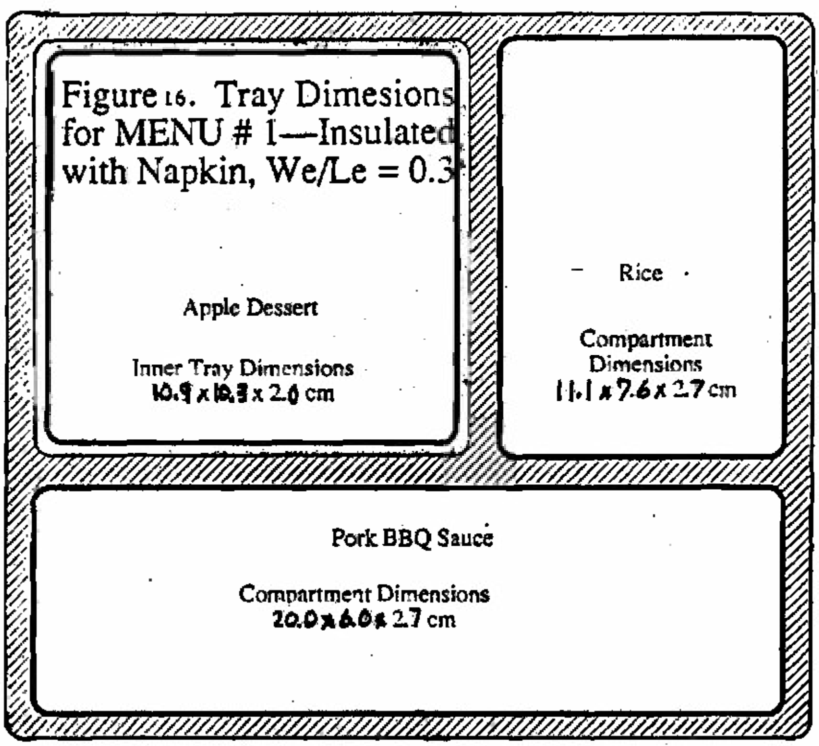

Figure 16. Tray Dimensions for MENU #1 (W_e/L_e=0.3)

In preparation for Phase II prototype testing, it was determined that thermoforming molds would be made to fabricate the tray designs shown in Figures 11, 14, 15 and 16. These designs were selected because they best represented the various concepts presented in Phase I.

PHASE II

FABRICATION OF PROTOTYPE MOLDS AND TRAYS

INTRODUCTION

The objective of Phase II was to demonstrate the tray-design concepts, outlined in the Phase I report, by fabricating prototype molds and compartmented trays. Two variables were used in the design of prototype trays: the tray dimensions and the use of paper napkins as insulating material. Both of these variables were shown to affect heat penetration during the retort cycle. Retort experiments were conducted using the prototype compartmented trays to measure the temperature profiles and heat penetration values (F_p) for the food items in each compartment. Computer simulations were conducted on suggested menu combinations provided by Natick. Experimental data on the thermal diffusivity and density of the suggested foods, and the thermal conductivity of the napkin insulation material were also obtained. In order to accurately obtain experimental data on the thermal diffusivity of suggested food components, a simple method for measuring thermal diffusivities of homogeneous and nonhomogeneous foods was designed. A technical report was prepared on this method and is included in Appendix F. Towards the end of Phase II, the range of possible tray designs was narrowed to an optimal "one-tray design" which could be used to simultaneously thermal-process a wide variety of menus.

TECHNICAL APPROACH

A. PROTOTYPE MOLDS AND TRAYS

1. Materials Used:

Two thicknesses of high barrier plastic sheet stock material (PP/adhesive/EVOH/adhesive/PP) were used to fabricate the compartmented trays. The first sheet material had a total thickness of 28 mils and was obtained from the Quantum Chemical Corporation. The second material had a total thickness of 52 mils and was obtained from the American National Can Company. A trilaminate consisting of aluminum foil and plastic film was used as the lid material, and a commercial paper napkin was used as the insulation material.

2. Molds and Trays:

As a result of Phase I efforts, three tray designs which could be used for the simultaneous thermal processing of different foods were recommended: (1) a compartmented tray with a separate inner tray containing the dessert item, wherein the inner tray was constructed of a retortable plastic foam; (2) a compartmented tray with a separate inner tray containing the dessert item, wherein the inner tray was insulated with a paper napkin; and (3) a compartmented tray containing only low-acid foods in which no inner tray was required. With designs (1) and (2), selective heating of the food components would be achieved by designing proper tray dimensions and using insulation. With design (3), selective heating of food components would be achieved solely by designing proper tray dimensions.

Prototype trays were fabricated and heat-penetration measurements (F_p)

were taken to test only the second and third design concepts. The first design concept was not tested because of difficulties in obtaining suitable retortable foam materials. However, GE Plastics agreed to provide a polyphenylene oxide (PPO) foam material, and American Oil Company (Amoco) would provide an experimental retortable foam, as soon as both products became available.

Aluminum female molds and plug assists were fabricated by G&Q Associates to test the second and third design concepts. The molds were used to thermoform the coextruded sheet material into compartmented trays. Initial attempts at thermoforming resulted in trays that did not have very uniform thickness distribution nor dimensional stability, especially for those made of the thinner 28 mil material. Processing variables, such as dwell time, pressure and temperature were refined and better quality trays were formed with the 50 mil material.

B. THERMOPHYSICAL PROPERTIES

The computer program required the input of accurate data such as thermal diffusivity, thermal conductivity, and specific heat capacity of the foods which were to be processed in the compartmented trays. Although these values were predicted by the COST program in Phase I, actual experiments were conducted in Phase II to obtain this data on the foods provided by Natick. Experimental data on the thermal diffusivities of foods were obtained using a test method that was designed specifically for these homogeneous and nonhomogeneous foods (Appendix C). The experimental and predicted thermal diffusivity values for foods at three different temperatures are compared in Table 1. The values are relatively close in comparison. The thermal conductivity of the insulating napkin is reported in Appendix D, and the bulb

densities are reported in Appendix E. A technical report written on the method for measuring thermal diffusivities of homogeneous and nonhomogeneous foods is provided in Appendix F.

Table 1. Comparison of Experimental and Predicted Thermal Diffusivity

	40 °C		60 °C		80 °C	
Food	Experimental	Predicted	Experimental	Predicted	Experimental	Predicted
Apple dessert	1.33	1.46	1.34	1.54	1.34	1.62
Chicken stew	1.51	1.46	1.48	1.54	1.43	1.62
Chocolate pudding	1.35	1.44	1.31	1.51	1.24	1.58
Pork withBBQ sauce	1.28	1.41	1.26	1.49	1.22	1.56
Potato augratin	1.42	1.48	1.38	1.56	1.37	1.65
Rice w/butter sauce	1.38	1.44	1.36	1.52	1.37	1.59
Sliced peaches	1.47	1.50	1.45	1.59	1.48	1.67
Tuna noodles	1.43	1.43	1.40	1.50	1.39	1.58

C. HEAT PENETRATION EXPERIMENTS

1. Tray Preparation and Retort Experiment:

Preparing a compartmented tray for heat penetration measurement was difficult and time consuming, especially when it contained an inner tray. A thermocouple had to be positioned carefully at the geometric center of each compartment for monitoring the temperature history. An electric hand iron was used to heat-seal lids on the compartmented tray and the inner tray.

The STOCK rotary retort located in the Rutgers Food Science pilot plant was used for thermal processing the trays. Real-time heat penetration data was integrated by an 8-channel data acquisition program to obtain the lethality values for the food in each compartment. The retort cook and cool temperatures were 121^{o}C and 26.1^{o}C, respectively.

2. Experimental Results and Discussion:

Experiments were conducted to test the validity of the computer program. Shown in Table 2 are the target, predicted and experimental F_p values for a meal consisting of pork BBQ sauce, rice and apple dessert. The temperature history curve of this meal is also shown in Figure 1. The dessert item was contained in an inner tray which was insulated with a napkin.

Table 2. Comparison of Target, Predicted and Experimental F_p Values

	Target	Predicted	Experimental	(Standard Deviation)
F_{pe}	6.1	7.9	6.2	(0.6)
F_{ps}	6.1	6.1	8.5	(0.4)
F_{pd}	3.1	7.6	4.7	(1.8)
Highest dessert temperature reached		100.1°C	95.3°C	

F_p values

Target:	Desirable F_p value
Predicted:	F_p value obtained from computer simulations
Experimental:	Average F_p value obtained from three experiments

Menu Items

Entree:	Pork BBQ sauce, F_{pe} based on 121.1 °C and z=10 °C
Starch:	Rice with butter sauce, F_{ps} based on 121.1 °C and z=10 °C
Dessert:	Apple dessert, F_{pd} based on 100.0 °C and z=10 °C

Tray Design and Dimensions

Compartment with an inner tray insulated by a napkin

Entree compartment:	21.1 x 5.3 x 3.0 cm
Starch compartment:	7.8 x 9.8 x 3.0 cm
Dessert compartment:	12.5 x 9.8 x 3.0 cm
Inner tray:	11.6 x 9.0 x 2.2 cm.

Processing Conditions

Thermal processing time =	40 minutes
Retort temperature =	121.1°C
Cooling temperature =	26.1 °C
Initial temperature of pork BBQ sauce =	25.2 °C
Initial temperature of rice with butter sauce =	25.6 °C
Initial temperature of apple dessert =	25.3 °C

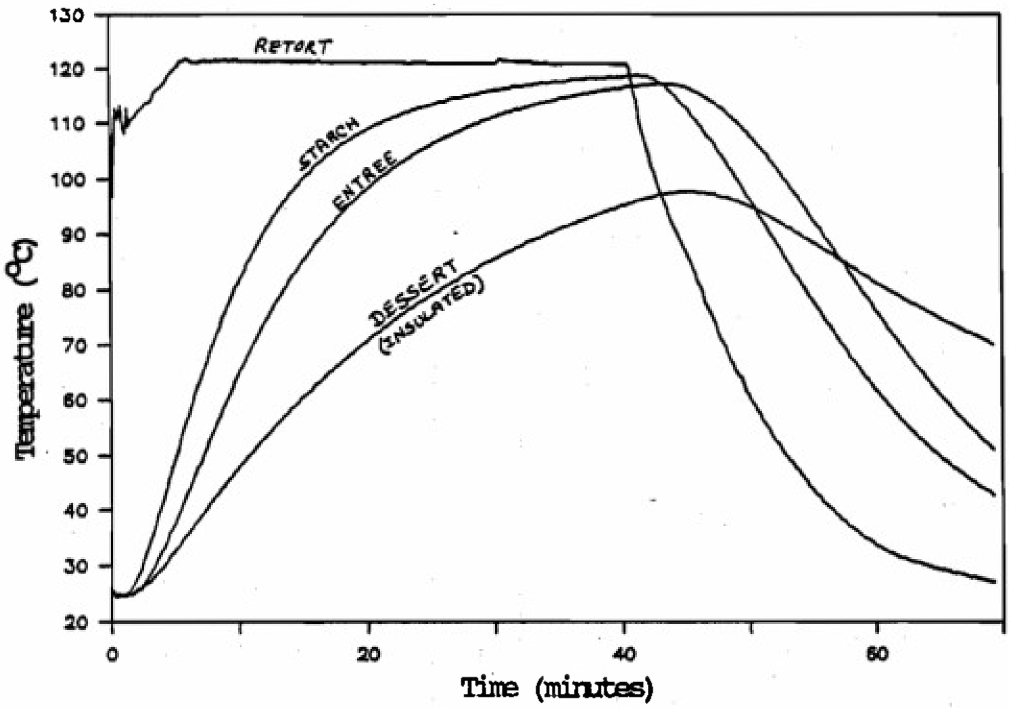

Figure 1. Temperature History Curve for Meal Consisting of Pork BBQ Sauce, Rice with Butter Sauce, Apple Dessert

The experimental lethality value for the entree, F_{pe}, and for the starch, F_{ps}, deviated from the predicted values by as much as 40%. It is not too surprising that this deviation in values occurred when considering the following factors that may have influenced the results:

a. Thermal processing of retortable plastic trays is a relatively little understood process compared to thermal processing of metal cans;

b. The computer program assumes the compartment to be rectangular, but the actual tray has round corners and tapered edges making its volume slightly smaller;

c. Plastic trays are not as rigid as metal cans, and their dimensions will more likely change (expand and contract) during the different stages of the retort process;

d. Since the compartments have low profiles (less than 4 cm), a small displacement of the thermocouple from its proper position will cause a significant error in the F_p value;

e. Insertion of an inner tray with a napkin into the compartmented tray makes accurate placement of the thermocouple more difficult;

f. Due to the nature of the thermoforming process, the wall thickness is not uniform for the entire tray (i.e., the wall thickness is thinner at the corners and inner edges);

g. The computer program does not take into account any inhomogeneity of food;

h. The thermal history is strongly affected by the amount of headspace;

i. Since the retort was operated manually, there may have been some variation among runs due to the operator (accurate control of the cooling phase is particularly important);

j. Accurate thermophysical properties of food and the tray material are required for the program;

k. Accurate convective heat transfer coefficient is also required.

Since the computer program was thoroughly debugged and the heat transfer equations used in the program were based on well-established principles, the computer program should have produced reasonable predictions when accurate thermophysical properties were provided. Therefore, the strategy at this point was to conduct more experiments to identify the major factors which affected the thermal processing of foods in this new kind of retortable plastic compartmented tray. The aim was to control these factors as much as possible, and to have a better understanding of the magnitude of experimental variation

to be expected, so that ultimately, the trays could be properly designed.

An experiment was also conducted to verify whether the geometric center was indeed the coldest spot in the starch compartment. To avoid any variation due to inhomogeneity of food, a 10% bentonite solution was placed in the starch compartment. Three thermocouples were placed in the starch compartment, one at the geometric center, and the other two at 0.6 cm to the right and left of the geometric center. Figure 2 shows the thermal history curve of this experiment. The F_p values obtained are 10.1 (left), 9.7 (center) and 10.2 (right), demonstrating that the geometric center was indeed the coldest spot.

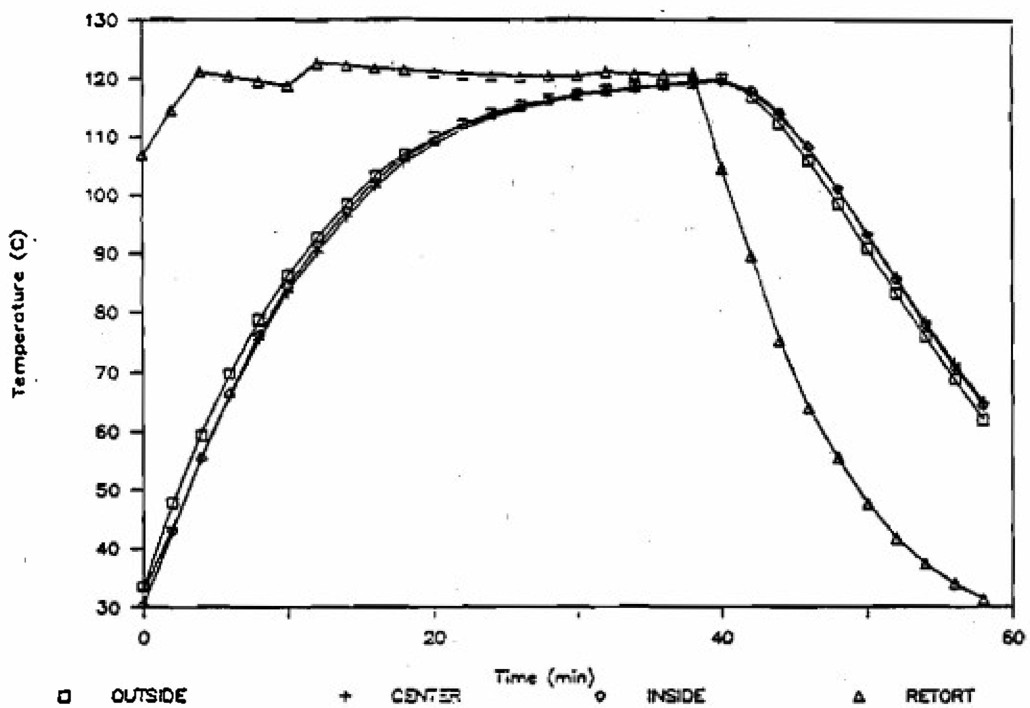

Figure 2. Temperature History

(10% Bentonite in Starch Compartment)

3. Computer Simulations:

The computer program was modified with an optimization subroutine to include the use of the f and j value method.[3,4] A part of the program was also rewritten to improve the computation speed. The average computation time for simulating the retort process of a three-component menu was reduced from 12 hours to about 5 hours. The revised flowchart and program codes are provided in Appendix G.

Table 3 lists the optimal tray dimensions, obtained from computer simulations, for some of the menu combinations suggested by Natick. Two sets of dimensions were provided: the first set considered only the design constraints, such as maximum allowable dimensions, and the second set considered not only the design constraints but assumed a small headspace. Note that some F_p values in the table exceeded the required values of 6 to 8. This may have been the result of the objective function and the constraints (such as tray dimensions) imposed on the computer program. Also, the food items in the menu had such vastly different thermal properties that it was difficult to simultaneously thermoprocess them in a tray with reasonable dimensions.

Table 3. Optimal Tray Dimensions from Simulation Program

Using f & j Value Concept

		Original design constraints				Considering headspace & edge of inner dessert tray			
meal #	Food	X, m	Y, m	Z, m	Fp, min	X, m	Y, m	Z, m	Fp, min
1	Pork BBQ sauce	0.2352	0.0492	0.0282	6.2	0.2287	0.0686	0.0299	6.0
	Rice butter sauce	0.0869	0.0926	0.0282	6.1	0.0729	0.1497	0.0299	8.3
	Apple dessert	0.1403	0.0926	0.0282		0.1478	0.1497	0.0299	
	inner dessert tray	0.1323	0.0847	0.0202	15	0.1358	0.1377	0.0199	20.8
	time for heating phase: 41.9 minutes					time for heating phase: 37.7 minutes			
2	Pot w/ bacon	0.2069	0.0652	0.0242	6.1	0.2469	0.0741	0.0265	6.1
	Applesauce	0.0785	0.1197	0.0242	6	0.0865	0.1471	0.0265	6.1
	Corn wk d	0.1205	0.1197	0.0242		0.1524	0.1471	0.0265	
	inner dessert tray	0.1139	0.1131	0.0176	3.1	0.1404	0.1351	0.0197	3.1
	time for heating phase: 28.6 minutes					time for heating phase: 24.2 minutes			

(continue)

Table 3. (continued)

3	Chili	0.2045	0.0603	0.0264	10	0.2297	0.0689	0.0297	9.1
	Rice	0.0744	0.1154	0.0264	6.1	0.0735	0.1499	0.0297	6.1
	Peach slices	0.1221	0.1154	0.0264		0.1482	0.1499	0.0297	
	inner dessert tray	0.1142	0.1075	0.0185	21.7	0.1362	0.1379	0.0199	17.0
	time for heating phase: 38.6 minutes					time for heating phase: 34.4 minutes			
4	Chicken stew	0.2137	0.0581	0.0262	11.5	0.2286	0.0686	0.0297	10.0
	Pears sliced	0.0777	0.1113	0.0262	6.1	0.0729	0.1497	0.0297	6.0
	Chocolate pudding	0.1281	0.1113	0.0262		0.1477	0.1497	0.0297	
	inner dessert tray	0.1201	0.1033	0.0183	258.3	0.1357	0.1377	0.0199	198.8
	time for heating phase: 43.3 minutes					time for heating phase: 38.6 minutes			
5	Beef pepper steak	0.2130	0.0611	0.0251	13.3	0.2286	0.0686	0.0299	12.7
	Potato augratin	0.0765	0.1183	0.0251	6	0.0728	0.1498	0.0299	6.2
	Fruit mix	0.1285	0.1183	0.0251		0.1477	0.1498	0.0299	
	inner dessert tray	0.1205	0.1103	0.0171	168.6	0.1357	0.1378	0.0200	136.0
	time for heating phase: 38.6 minutes					time for heating phase: 37.0 minutes			
6	Spaghetti /meat sauce	0.2056	0.0601	0.0264	16.9	0.2286	0.0686	0.0297	15.2
	pears sliced	0.0747	0.1151	0.0264	6	0.0729	0.1497	0.0297	6.0
	Chocolate pudding	0.1229	0.1151	0.0264		0.1477	0.1497	0.0297	
	inner dessert tray	0.1149	0.1071	0.0184	248.7	0.1357	0.1377	0.0199	198.8
	time for heating phase: 43.3 minutes					time for heating phase: 38.6 minutes			
7	Chicken ala king	0.2007	0.0623	0.0261	11.7	0.2299	0.0690	0.0296	11.1
	Rice	0.0726	0.1198	0.0261	6.1	0.0736	0.1499	0.0296	6.2
	Peach slices	0.1200	0.1198	0.0261		0.1483	0.1499	0.0296	
	inner dessert tray	0.1121	0.1119	0.0181	21	0.1363	0.1379	0.0199	17.5
	time for heating phase: 37.9 minutes					time for heating phase: 34.4 minutes			
8	Beef stew	0.2009	0.0609	0.0266	16.6	0.2286	0.0686	0.0297	15.0
	Fruit mix	0.0731	0.1164	0.0266	6.1	0.0729	0.1497	0.0297	6.0
	Chocolate pudding	0.1266	0.1164	0.0266		0.1477	0.1497	0.0297	
	inner dessert tray	0.1187	0.1085	0.0187	247.4	0.1357	0.1377	0.0199	196.9
	time for heating phase: 43.7 minutes					time for heating phase: 38.6 minutes			
9	Ham slices	0.2003	0.0558	0.0292	12.5	0.2310	0.0693	0.0294	10.7
	Potato au gratin	0.0743	0.1046	0.0292	6	0.0745	0.1495	0.0294	6.2
		0.1180	0.1046	0.0292		0.1484	0.1495	0.0294	
	inner dessert tray	0.1101	0.0967	0.0213	20.2	0.1364	0.1375	0.0199	19.7
	time for heating phase: 45.1 minutes					time for heating phase: 36.3 minutes			
10	Tuna & noodles	0.2625	0.0373	0.0333	6.1	0.2298	0.0689	0.0297	6.2
	Peach slices	0.0992	0.0686	0.0333	6.1	0.0735	0.1499	0.0297	11.7
	Green beans	0.1553	0.0686	0.0333		0.1482	0.1499	0.0297	
	inner dessert tray	0.1474	0.0607	0.0254	3.7	0.1362	0.1379	0.0199	17.2
	time for heating phase: 38.9 minutes					time for heating phase: 34.4 minutes			
11	Hamburger	0.2050	0.0789	0.0202	13.9	0.2326	0.0948	0.0230	9.2
	Rice	0.0985	0.1142	0.0202	6.1	0.1123	0.1366	0.0230	6.0
	Carrots	0.0985	0.1142	0.0202	22.9	0.1123	0.1366	0.0230	9.7
	time for heating phase: 36.8 minutes					time for heating phase: 23.8 minutes			
	* No high acid food in the meal; no inner tray required.								
12	Chix br/gravy	0.2226	0.0731	0.0201	12.3	0.2430	0.0902	0.0231	11.0
	Potato augratin	0.1073	0.1054	0.0201	6.1	0.1175	0.1299	0.0231	6.0
	Green peas	0.1073	0.1054	0.0201	12.9	0.1175	0.1299	0.0231	11.4
	time for heating phase: 30.7 minutes					time for heating phase: 25.6 minutes			
	* No high acid food in the meal; no inner tray required.								

** The reference temperature for calculating the lethality values (Fp's) of dessert in meals #1 to #10 is 100 degreesC.

*** The reference temperature for all other foods is 121.1 degreesC.

To correct these problems, different dimensional constraints were imposed on the computer program in an attempt to locate better results in the simulation for a compartmented tray. Listed in Table 4 are these new design constraints.

Table 4. Design Constraints for Compartmented Tray Simulation

Insulation thickness:	0.0 - 0.6 cm	(0 0.236 in)
height of tray:	2.1 - 3.6 cm	(0.827 - 1.47 in)
length of tray:	16.6 - 31.6 cm	(6.54 - 12.44 in)
width of starch compartment:	8 - 20 cm	(3.15 - 7.87 in)
depth of dessert inner tray:	1.5 - 3.0 cm	(0.591 - 1.181 in)
heating time:	10 - 200 minutes	
retort temperature:	121.1°C	
cooling water temperature:	20°C	
target lethality value, F_p:	entree - 6.1 at ref. temp 121.1°C	
	starch - 3.1 "	
	dessert - 3.1 at reference temp 100°C	
weight/volume of compartment*:	entree - 11 oz / 375 cc	
	starch - 8 oz / 261 cc	
	dessert - 8 oz / 261 cc	

* The volume shown has taken into consideration extra space required to compensate for the tapered corner of each compartment and a free volume with about 0.6 cm (0.236 inch) height above each food item to allow for safe filling and sealing.

D. ONE-TRAY DESIGN

In addition to applying new constraints to the computer program, the feasibility of using an alternative tray design (such as different arrangements of the compartments) was also investigated. It was determined that although several tray designs could be used to process different menus, it would be more economical to have a single tray design in which a variety of different menus could be simultaneously thermoprocessed. Therefore, computer simulations were

conducted to test the feasibility of the universal "one-tray design," i.e. using an outer tray to thermal process all low-acid foods, or using that same outer tray with another inner tray (with napkin insulation) to thermoprocess a combination of low- and high-acid foods (Figure 3). The computer simulations showed that such a tray design is theoretically possible to use for processing the most recent menu combinations provided by Natick (Table 5).

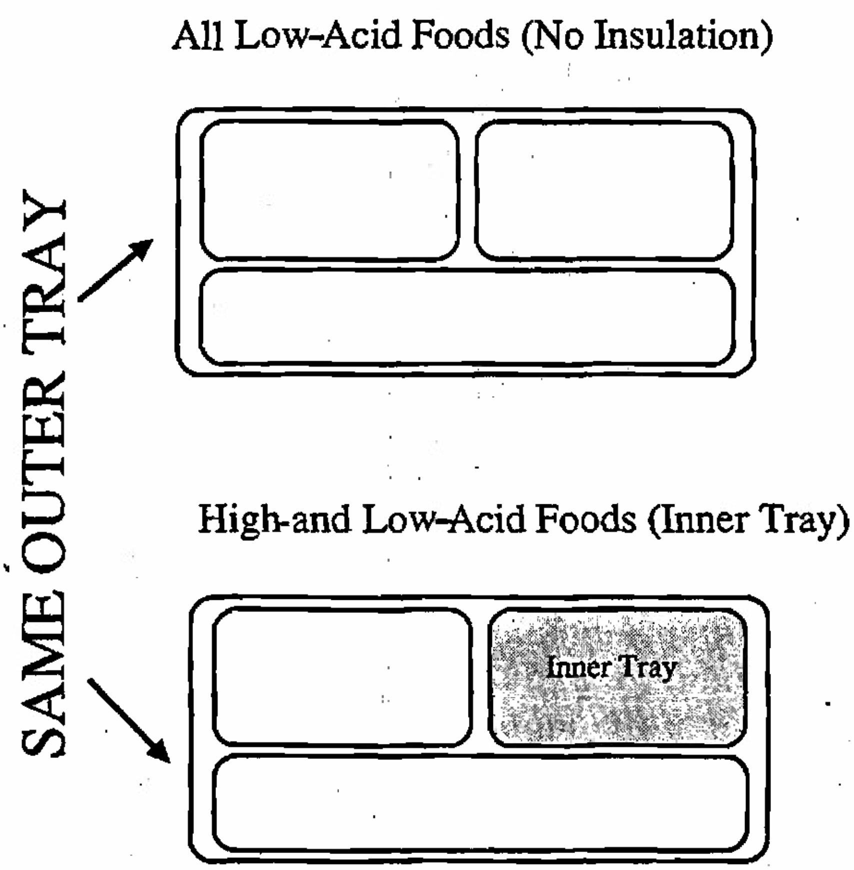

Figure 3. One Tray Concept

Table 5. Suggested Menus

LUNCH AND/OR DINNER MENU

MEAL #1
Chicken Breast in Gravy
Green Beans
Apple Dessert

MEAL #2
Hamburger Patties
Corn
Chocolate Pudding

MEAL #3
Chili con Carne
"Buttered" Rice
Peach Slices

MEAL #4
Beef Stew
Potatoes in "Butter"
Chocolate Pudding

MEAL #5
Tuna Noodle Casserole
Green Beans
Apple Dessert

MEAL #6
Chicken ala King
"Buttered" Rice
Peach Slices

MEAL #7
Ham Slices
Potatoes in "Butter"
Apple Dessert

MEAL #8
Spaghetti w/ Meat Sauce
Corn
Chocolate Pudding

MEAL #9
Pork/BBQ Sauce
"Buttered" Rice
Apple Dessert

MEAL #10
Chicken Stew
Green Peas
Chocolate Pudding

MEAL #11
Beef Pepper Steak
Sliced Carrots
Fruit Mix

MEAL #12
(alt bkft)
Diced Ham & Potatoes
Corn
Applesauce

BREAKFAST MENUS

MEAL #1
Bread Pudding w/ Sausage
Hominy Grits
Peach Slices

MEAL #2
Ham Omelet
Potatoes in "Butter"
Pear Slices

MEAL #3
Corned Beef Hash
Hominy Grits
Apple Dessert

MEAL #4
Western Omelet
Potatoes in "Butter"
Fruit Mix

DISCUSSION

In Phase II, prototype aluminum molds with plug assists were successfully fabricated and used to produce compartmented trays. Experiments were conducted to measure thermal properties of food samples, specifically their thermal diffusivity, thermal conductivity and specific heat capacity. Heat penetration measurements were taken on components of a sample meal that was packaged and processed in retortable compartmented trays, and these values were compared to the targeted and predicted values. Although experimental heat penetration values for the entree and starch components differed significantly from the predicted values, measures were taken to identify and control the sources of these variations. The cold spot in the starch compartment was measured to be at the geometric center. The computer program was improved for faster computation, and the "f and j value method" was incorporated for the optimization subroutines. Computer simulations, conducted on four sample menu combinations, resulted in two types of tray designs; the first design which had no dimensional constraints, and the second design which considered such constraints as tray dimensions and a small allowable headspace. The second simulation was further modified to apply other constraints including allowable dimensions of each compartment, heating time, and retort cook and cool temperatures. This simulation resulted in a more reasonably shaped tray design which was then refined with actual experimentation. The result was the establishment of a universal "one-tray design" concept, in which a variety of meals, consisting of three components, could be simultaneously thermal processed. If the meal consisted of both low- and high-acid foods, the most heat-sensitive component would be packaged in an inner tray that would require proper insulation to protect it from overprocessing.

PHASE III

FABRICATION OF 200 COMPARTMENTED TRAYS FOR SIMULTANEOUS THERMOPROCESSING OF FOODS

INTRODUCTION

The objective of Phase III was to further test and finalize the "one-tray design" of a compartmented tray which may be used to simultaneously thermoprocess a variety of menus, each containing three different foods, and to fabricate 200 trays of this type with hermetically sealable lids. A unique feature of this universal design was the use of an inner tray and paper napkin to protect the most heat-sensitive food component during processing, if necessary. Efforts involved in Phase III included conducting computer simulations on various one-tray designs to generate optimal dimensions, fabricating trays, conducting retort experiments using these trays, and conducting microbiological tests to verify commercial sterility of retorted products. In addition to this, a study was also conducted to determine the effect of the gap space between the tray compartments on heat penetration during the retort process. The result of this study provided helpful indications of how accurate some of the assumptions made by the computer programs were. Ultimately, a universal one-tray design was finalized and 200 trays were fabricated.

TECHNICAL APPROACH

A. COMPUTER SIMULATIONS

A computer program titled OP3.F was written to simulate thermal processing of foods in the one-tray design. This program and related output is provided in Appendix H. Computer simulations were conducted using this program to test the feasibility of the one-tray design, i.e. using just one outer tray to thermal process all low-acid foods, or using the same outer tray with an insulated inner tray to thermal process a combination of high- and low-acid foods. Resulting output from the computer simulations demonstrated that such a design was possible and could be used to simultaneously thermal process the menu items previously suggested by Natick during Phase II. This design used a paper napkin to wrap around the inner tray to protect the heat-sensitive food during retorting. The computer program output described the predicted processing parameters for each menu and is listed in Table 1.

B. TRAY FABRICATION

The final tray design was based on the two variables used in the design of previous prototype trays: the tray dimensions and use of the paper napkin as an insulator (Figure 1), and the results of tests conducted on the one-tray design prototypes.

Table 1. Computer Simulation for One-Tray Design

Menu	Food item	Vol. (ml)	Fpp (min)	Fpt (min)	Insu. (mm)	Heat time (min)
1	chicken stew	229.8	6.3	6.0		28.2
	potatoes au gratin	170.0	6.1	6.0		
	apple dessert	223.1	3.1	3.0	4.0	
2	tuna noodle casserole	233.1	6.4	6.0		28.4
	chili con carne	170.8	6.1	6.0		
	peach slice	225.2	3.1	3.0	3.9	
3	chicken stew	232.4	6.1	6.0		28.2
	potatoes augratin	170.1	6.1	6.0		
	chocolate pudding	228.2	8.6	8.5		
4	chicken breast/gravy	231.9	6.2	6.0		28.6
	green beans	189.0	6.1	6.0		
	apple dessert	227.0	3.1	3.0	4.0	
5	hamburger patties	228.8	6.1	6.0		28.2
	corn	186.9	6.0	6.0		
	chocolate pudding	227.0	8.7	8.5		
6	beef stew	231.4	6.1	6.0		28.2
	potatoes in butter	170.1	6.0	6.0		
	chocolate pudding	228.4	8.5	8.5		
7	tuna noodle casserole	232.6	6.2	6.0		28.4
	green beans	189.0	6.1	6.0		
	apple dessert	227.0	3.0	3.0	3.9	
8	chicken ala king	233.9	6.5	6.0		29.1
	buttered rice	193.0	6.1	6.0		
	peach slices	226.6	3.1	3.0	4.0	
9	ham slices	227.0	6.2	6.0		31.0
	potatoes in butter	185.0	6.3	6.0		
	apple dessert	241.4	3.9	3.0	4.0	
10	spaghetti/meat sauce	227.0	6.1	6.0		27.5
	corn	182.4	6.1	6.0		
	chocolate pudding	222.0	8.6	8.5		
11	pork/BBQ sauce	227.0	6.2	6.0		27.9
	buttered rice	185.9	6.1	6.0		
	apple dessert	221.4	3.0	3.1	4.0	
12	chicken stew	227.0	6.1	6.0		27.6
	green peas	174.0	7.2	7.2		
	chocolate pudding	224.0	8.5	8.5		
13	beef pepper steak	227.0	6.0	6.0		27.9
	sliced carrots	184.7	6.1	6.0		
	fruit mix	215.4	3.3	3.0	4.0	

* Tray dimensions (m):

Entree	0.1858	0.0558	0.0300
Starch	0.0705	0.1203	0.0300
Outer dessert	0.1073	0.1203	0.0300
Inner dessert	0.0993	0.1123	0.0240
Headspace			0.0060
Sealing edge for inner tray			0.0040

** The reference temperature for calculating Fp's of fruits and other foods is 100°C and 121.1°C separately.

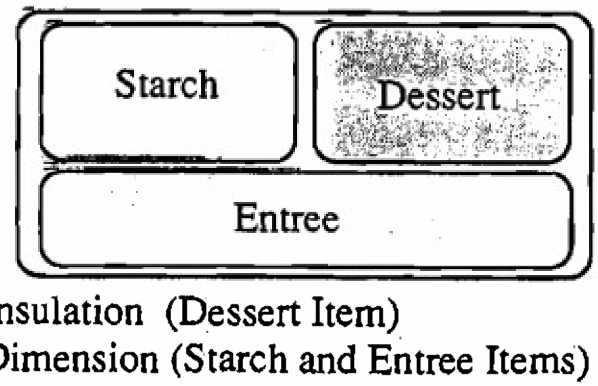

Figure 1. Two Design Variables for One-Tray Design

The dimensions of the final compartmented tray, with inner tray, are shown in Figure 2. Two hundred trays of this design, including both outer compartmented trays and inner trays, were fabricated by G&Q Associates for retort and microbiological experiments. The outer trays were thermoformed from a multilayer coextruded material consisting of PP outer and inner layers, and a high-barrier EVOH middle layer. The EVOH provides the food the with good protection against gas and vapor transmission. The inner trays were thermoformed from a PP material. Both inner and outer trays were hermetically sealed with a trilaminate lidding material composed of polyester (PY) outer layer, aluminum foil middle layer, and a PP heat-sealant layer. Insulating paper napkins were used with the trays containing meals that consisted of low- and high-acid foods. The paper napkin serves not only as an inexpensive, environmentally friendly insulating material, which protects the heat-sensitive food inside the inner tray during retorting, but also as a napkin for the soldier during meal time.

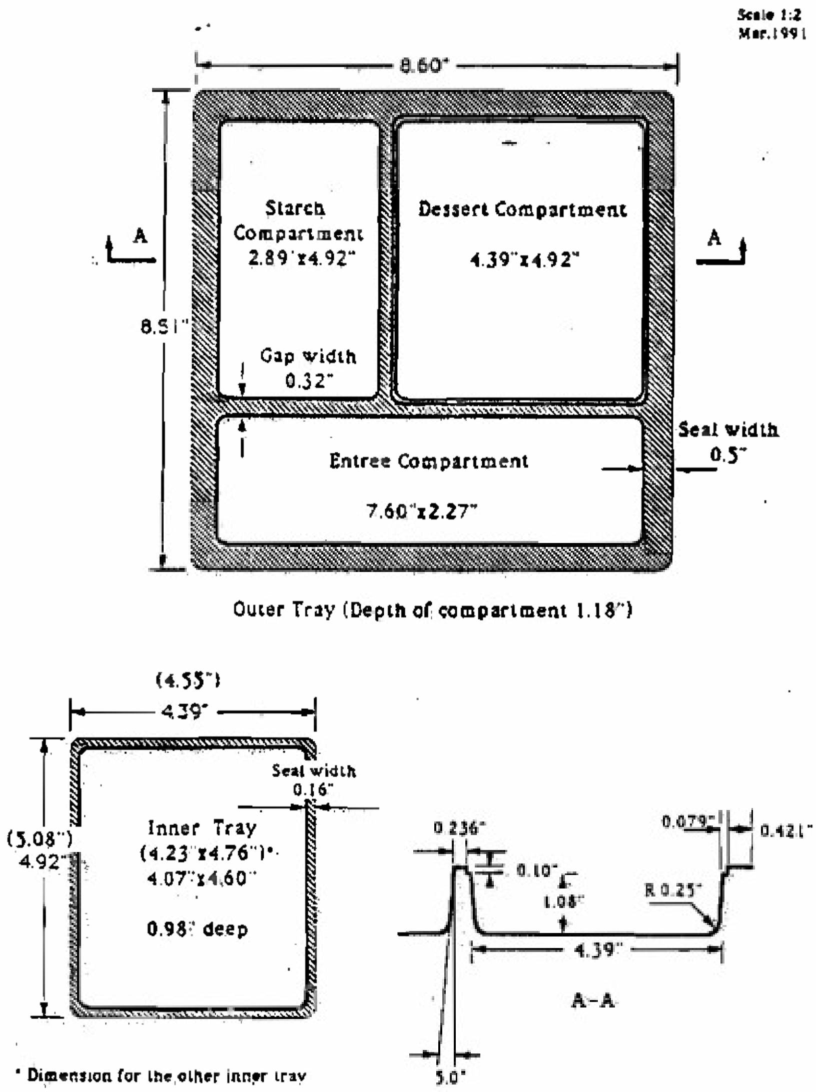

Figure 2. Dimensions for One-Tray Design

C. RETORT EXPERIMENTS AND RESULTS

Retort experiments were conducted on menu's 1, 2 and 3 (see Table 1), to compare experimental heat penetration (F_p) values generated by the computer simulations conducted on this one-tray design. Table 2 summarizes the F_p values obtained from the retort experiment and compares these values to those predicted by the computer simulation. The experimental F_p values correlated well with predicted values, with the exception of the dessert component in Menu 3. The observed differences in experimental and theoretical F_p values for the dessert item is somewhat deceptive. The reference temperature for

calculating the F_p values for the dessert item was 100°C instead of 121°C used for the entree and starch items. As a result, the difference in F_p value was somewhat inflated. The observed difference might also be contributed by the factors listed on pages 35 and 36 of this report. However, the overall correlation of the F_p values indicates that accurate predictions may be made using the computer program. The time/temperature profiles for Menu 2 obtained during the retort experiment are depicted in Figure 3, and the corresponding time/temperature data is recorded in Table 3.

Table 2. Summary of One-Tray Design

Menu		I	II	III
Food item	entree	chicken stew	tuna noodle	chicken stew
	starch	potato eugretin	chili con carne	poteto augretin
	dessert -	apple dessert	peach slice	chocolate pud.
Computer generation	insulation(mm)	4.0	3.8	0
	heet time(min)	28.2	28.4	28.2
	F_p target (En/St/De)(min)	6.0/6.0/3.0	6.0/6.0/3.0	6.0/6.0/8.5
	F_p predicted(min)	6.3/6.1/3.1	6.1/6.0/3.1	6.1/6.1/8.6
Experiment	Vol.(cm³) En	229.8	233.1	232.4
	St	170.9	170.8	170.1
	De	223.1	225.2	228.2
	insulation(layer)	4(bensei)	4	0
	heat time(min)	28 - 30	28 - 30	28 - 30
	F_p (min) entree	7.1+-0.1	6.2+-0.4	7.4+-1.0
	starch	8.2+-0.4	6.6+-0.7	6.4+-0.4
	dessert	3.2+-0.2	4.4.+-0.5	13.4+-0.6

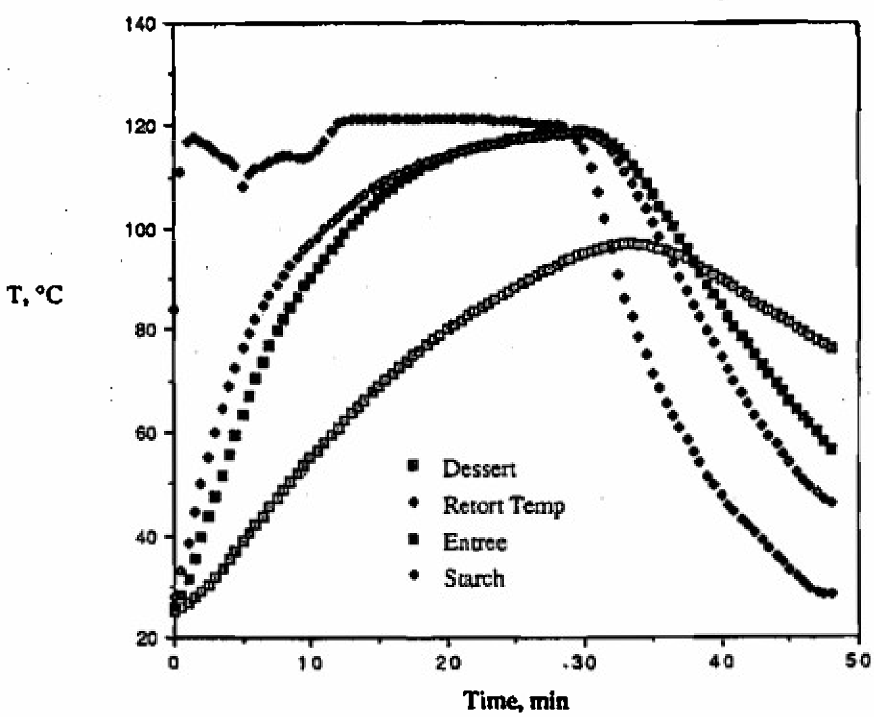

Figure 3. Temperature Profiles for MENU #2

Table 3. Time-Temperature Record for MENU #2

	A	B	C	D	E	F	G		H
1								1	
2				(April 24,1991)				2	
3								3	
4	TIME/min	T/De/C	T/RT/C	T/En/C	T/St/C	F/De	F/En	4	F/St
5	0	25.12	84.11	25.85	27.9	(min)	(min)	5	(min)
8	0.5	25.76	111.11	28.3	32.91			6	
7	1	26.66	117.06	31.63	38.6			7	
8	1.5	27.78	117.64	35.64	44.51			8	
9	2	29.05	117.15	39.86	60.1			9	
10	2.5	30.4	118.04	43.72	55.22			10	
11	3	31.9	115.15	47.57	60.12			11	
12	3.5	33.57	113.99	51.53	64.75			12	
13	4	35.28	113.4	55.5	88.98			13	
14	4.5	37.1	112.35	59.54	72.85			14	
15	5	38.96	108.18	63.53	76.51			15	
16	5.5	40.67	110.72	67.28	79.6			18	
17	6	42.28	111.77	70.72	82.29	F/De	F/En	17	F/St
18	6.5	43.95	112.44	73.9	84.78	0	0	18	0
19	7	45.56	113.1	76.84	87	1.8E-06	1.92E-05	19	0.000199
20	7.5	47.24	113.76	79.61	89.09	4.45E-06	5.55E-05	20	0.000521
21	8	48.95	114.17	82.16	91	8.37E-06	0.000121	21	0.001021
22	8.5	50.58	114.07	84.48	92.74	1.41E-05	0.000232	22	0.001768
23	9	52.16	113.89	86.71	94.37	2.23E-05	0.000418	23	0.002854
24	9.5	53.68	113.85	88.79	95.92	3.4E-05	0.000719	24	0.004406
25	10	55.15	114.34	90.69	97.27	5.03E-05	0.001185	25	0.008524
26	10.5	56.62	115.31	92.46	98.59	7.33E-05	0.001884	28	0.009395
27	11	58.08	116.91	94.24	99.95	0.000105	0.002939	27	0.013321
28	11.5	59.53	118.83	95.86	101.17	0.00015	0.00447	28	0.018521
29	12	60.95	120.4	97.56	102.47	0.000213	0.006734	29	0.025535
30	12.5	82.41	121.1	99.18	103.71	0.0003	0.010022	30	0.034867
31	13	63.77	121.36	100.7	104.86	0.000419	0.014689	31	0.047028
32	13.5	85.15	121.38	102.15	105.95	0.000582	0.021205	32	0.062658
33	14	86.44	121.47	103.46	106.92	0.000803	0.030014	33	0.0822
34	14.5	67.78	121.49	104.73	107.84	0.001103	0.041817	34	0.106353
35	15	69.03	121.53	105.9	108.89	0.001502	0.057288	35	0.135728
38	15.5	70.26	121.45	106.98	109.46	0.002033	0.077082	36	0.1708
37	16	71.45	121.44	108	110.18	0.002732	0.102142	37	0.212197
38	16.5	72.82	121.42	108.97	110.81	0.003646	0.133472	38	0.260057
39	17	73.78	121.47	109.89	111.42	0.004839	0.172195	39	0.315134
40	17.5	74.9	121.46	110.72	111.99	0.006385	0.219073	40	0.377936
41	18	76	121.46	111.48	112.53	0.008375	0.274917	41	0.449052
42	18.5	77.06	121.47	112.21	113.03	0.010916	0.340981	42	0.528846
43	19	78.09	121.53	112.87	113.49	0.014137	0.417889	43	0.617555
44	19.5	79.12	121.45	113.45	113.92	0.01822	0.505785	44	0.715498
45	20	80.13	121.47	114.01	114.37	0.023372	0.605778	45	0.824133
48	20.5	81.08	121.43	114.53	114.74	0.029754	0.71849	46	0.942429
47	21	81.97	121.52	114.95	115.09	0.037824	0.842647	47	1.070853
48	21.5	82.9	121.45	115.41	115.47	0.047373	0.980676	48	1.210602
49	22	83.76	121.41	115.79	115.77	0.059257	1.131328	49	1.36056
50	22.5	84.65	121.27	116.16	116.07	0.073844	1.295374	50	1.521243
51	23	85.48	121.22	116.52	116.35	0.091503	1.473599	51	1.692627
52	23.5	88.33	120.99	116.82	116.81	0.11298	1.884572	52	1.874585
53	24	87.12	120.95	117.1	116.83	0.138742	1.868262	53	2.065997
54	24.5	87.92	120.8	117.35	117.1	0.169714	2.084021	54	2.269687

(continue)

Table 3. (continued)

	A	B	C	D	E	F	G		H
55	25	88.67	120.8	117.58	117.26	0.206524	2.311515	55	2.481021
58	25.5	89.42	120.59	117.79	117.45	0.250273	2.55028	58	2.701807
57	28	90.13	120.57	117.99	117.64	0.301793	2.800297	57	2.932485
58	28.5	90.83	120.38	118.16	117.79	0.362323	3.060295	58	3.17123
59	27	91.53	120.37	118.3	117.94	0.433439	3.328811	59	3.418385
60	27.5	92.2	120.2	118.45	118.07	0.516418	3.606763	60	3.673051
81	28	92.84	120.14	118.55	118.16	0.612573	3.89119	61	3.933049
62	28.5	93.49	119.86	118.65	118.31	0.724252	4.182241	62	4.202184
63	29	94.13	118.5	118.78	118.42	0.853662	4.482137	63	4.478222
84	29.5	94.73	117	118.87	118.54	1.002245	4.788312	84	4.761995
65	30	95.27	115.29	118.86	118.5	1.170501	5.093783	65	5.043165
68	30.5	95.8	111.94	118.75	118.23	1.360596	5.391614	66	5.307388
67	31	98.2	107.14	118.31	117.54	1.569031	5.660749	87	5.532796
88	31.5	96.54	101.79	117.62	116.46	1.794439	5.890348	88	5.708577
89	32	96.82	98.13	116.68	115.01	2.034859	6.075262	89	5.83446
70	32.5	96.96	90.77	115.43	113.21	2.283155	6.213928	70	5.917631
71	33	97.07	86.17	114.06	111.21	2.53782	6.315079	71	5.970108
72	33.5	97.04	82.5	112.4	108.9	2.790733	6.384098	72	6.000938
73	34	96.94	78.71	110.6	106.47	3.037888	6.429699	73	6.018557
74	34.5	96.75	74.97	108.72	103.98	3.274464	6.459277	74	6.028487
75	35	96.48	71.57	106.65	101.31	3.496779	6.477641	75	6.033857
78	35.5	96.12	68.55	104.55	98.6	3.70141	6.488964	78	6.036734
77	36	95.69	65.65	102.45	95.87	3.88675	6.495946	77	6.038269
78	36.5	95.2	63.26	100.28	93.15	4.052315	6.500182	78	6.039089
79	37	94.67	60.82	98.12	90.41	4.19886	6.502758	79	6.039525
80	37.5	94.02	58.46	95.85	87.69	4.325034	6.504286	80	6.039759
81	38	93.33	55.91	93.55	85	4.432873	6.505185	81	6.039884
82	38.5	92.58	53.94	91.32	82.41	4.52324	6.505723	82	6.039954
83	39	91.81	51.47	89.08	79.79	4.599093	6.506045	83	6.039991
84	39.5	91.04	49.87	86.96	77.3	4.662621	6.506242	84	6.040013
85	40	90.17	47.79	84.79	74.76	4.714617	6.506362	85	6.040025
88	40.5	89.29	45.86	82.75	72.4	4.757076	6.506436	86	6.040031
87	41	88.37	44.42	80.72	69.99	4.79143	6.506483	87	6.040035
88	41.5	87.43	42.93	78.76	67.65	4.819097	6.506513	88	6.040038
89	42	86.52	41.79	76.84	65.43	4.841535	6.506532	89	6.040039
90	42.5	85.51	40.43	74.99	63.27	4.859316	6.506545	90	6.04004
91	43	84.58	39.04	73.17	61.3	4.87367	6.506553	91	6.040041
92	43.5	83.69	37.44	71.38	59.39	4.885364	6.506559	92	6.040041
93	44	82.83	35.96	69.56	57.52	4.894958	6.506562	93	6.040041
94	44.5	82.02	34.54	67.8	55.69	4.902919	6.506565	94	6.040041
95	45	81.21	33.23	66.05	53.93	4.909525	6.506566	95	6.040041
98	45.5	80.39	31.97	64.38	52.24	4.914995	6.506567	96	6.040041
97	46	79.55	30.78	62.71	50.81	4.919503	6.506568	97	8.040041
98	46.5	78.71	29.6	61.5	49.37	4.923218	6.506569	98	6.040041
99	47	77.9	28.81	59.92	48.04	4.926301	6.506569	99	6.040042
100	47.5	77.07	28.29	58.2	46.92	4.928848	6.506569	100	8.040042
101	48	76.26	28.16	56.46	45.99	4.930961	6.506569	101	6.040042

D. MICROBIOLOGICAL TESTS AND RESULTS

An inoculation and incubation study was conducted to verify that commercial sterility of food in each compartment was achieved during retorting. A three-compartment tray was filled with corned beef hash, rice in butter sauce and potatoes au gratin for testing. Initially, 10^4 spores (*Clostridium sporogenes* PA 3679, D_{250}=2.4 min) were inoculated in each food compartment. The tray was heat sealed and retorted at 121°C for 33 minutes. After retorting, the inoculated trays were incubated at 35°C.

After 2 weeks of incubation, the tray was opened aseptically and checked for any sign of spoilage. The contents were tested microbiologically as follows:

1. A 50 g ingredient was blended aseptically with a chilled sterile 450 ml peptone diluent (0.1% peptone).

2. Subsequent dilutions (10^{-1}, 10^{-2}, 10^{-3} and 10^{-4}) were made. These dilutions were plated on TSA plates in duplicate, and then incubated at 35°C for 4 days.

3. The dilutions were heat-shocked at 80°C for 30 minutes and inoculated into the following media:

a) Dextrose broth tubes containing bromothymol blue to detect any aerobic microorganism.

b) Cooked meat medium tubes to detect any anaerobic microorganism. The tubes were air-exhausted by placing them in a boiling water bath for 20 minutes prior to inoculation. The tubes were then inoculated from the above dilutions, and overlayed with 0.5% sodium-thioglycolate agar to exhibit anaerobic conditions. The tubes were then incubated at 35°C for 4 days.

Results: From outside observation, no swelling or sign of spoilage was noticed on the trays. At the end of the incubation period, no aerobic or anaerobic growth was noticed, which indicated that efficient heat treatment was applied on this product. It should be noted that the above study was conducted only one time.

E. GAP EFFECTS ON HEAT PENETRATION PARAMETERS

A study was conducted on the effects that the gap space between the tray compartments had on the effectiveness of the retort process. It was found that the gap spaces affected both the locations of the slowest heating point in each compartment and the apparent heat transfer coefficients. In the gap between compartments, convection was greatly reduced and the less heat was transferred through the gap sides. A technical report titled "Gap Effects on Heat Penetration Parameters of Multi-Compartment Tray" was written on the details and results of this study, and is contained in Appendix I. Overall, it was determined that a gap of at least 5 to 10 mm between compartments would allow for effective heat sealing and assure only small gap effects. When gap spaces are within this range, the geometric center of each compartment was still assumed to be the slowest heating point, and the apparent heat transfer coefficient remained practically unchanged.

CONCLUSIONS

At the completion of Phase III, Rutgers University, Department of Food Science, submitted the 200 compartmented trays, 200 inner trays, lidstock

material, thermoforming aluminum molds with plug assists, insulating napkin material and the computer simulation models to Natick, as required by the contract. The items were inspected by the Subsistence Protection Branch of the Food Engineering Directorate and were determined to be of high quality.

This document reports research undertaken at the U.S. Army Natick Research, Development and Engineering Center and has been assigned No. NATICK/TR-92/024 in the series of reports approved for publication.

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APPENDIX A

DESCRIPTION OF COMPUTER PROGRAM

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DESCRIPTION OF COMPUTER PROGRAM

Three separate programs (ANLYT-H3, ANLYT-F3, and MAIN-PL) are used to perform the following tasks:

1. Calculate the overall heat transfer coefficient from heating-sterilization experiments (ANLYT-H3).
2. Calculate the temperature history curve based on the overall heat transfer estimated from the previous step (ANLYT-F3).
3. Calculate the processing time in a retort operating at 250 °F of a compartmented tray containing low and high acid foods. Also calculated is the amount of insulation needed to protect the high acid food against overprocessing (MAIN-PL).

These three programs are currently being consolidated into a single program.

A. <u>Description for ANLYT-H3</u>

Title	1-20
Main program	30-410
Input parameters	30-190
Calculate overall heat transfer coefficient	200-410
Subroutines	
Define Biot Numbers (Bi) for 3 infinite slabs	800-870
Estimate first 20 positive roots of $a \tan a = Bi$	1000-1370
Calculate unaccomplished temperature change for each dimension	2000-2100
Calculate central temperature during heating and cooling	3000-4000
Calculate sums of square differences	4000-4200

The experimental heating curves are imported into the program through line 120.

B. <u>Description for ANLYT-F3</u>

Title	1-20
Main program	10-300
Parameter input	40-110
Subroutines	
Define Biot Numbers (Bi) for 3 infinite slabs	800-870

Estimate first 20 positive roots of $a \tan a = Bi$	1000-1370
Calculate unaccomplished temperature change for each dimension	2000-2100
Calculate central temperature during heating and cooling and store output file	3000-4000

C. Description for MAIN-PL

Title	1-20
Main program	30-340
Parameter input	30-130
Calculate process time for tray	150-260
Calculate insulation thickness (if needed)	275-340
Subroutines	
Rename variables	400-450
Calculate process time	500-599
Calculate insulation thickness	600-740
Define Biot Numbers (Bi) for 3 infinite slabs	800-870
Estimate first 20 positive roots of $a \tan a = Bi$	1000-1370
Calculate unaccomplished temperature change for each dimension	2000-2100
Calculate central temperature during heating and cooling	3000-4000
Calculate lethalities during heating and cooling	4000-4200

The program is linked through program line 77 to the software developed by the European Cooperation in Scientific and Technical Research for estimating the thermophysical properties of food .

DEFINITION OF PROGRAM VARIABLES

	1st ELEMENT (CO)
	2nd ELEMENT DIRECTION (I)
ALPHA (CO)	: (1D ARRAY) THERMAL DIFFUSIVITY OF FOOD IN CONTAINER CO (W/m^2 °K)
BI(SD)	: (1D ARRAY) BIOT NUMBER FOR DIRECTION (SD)
CCRIT	: CONVERGENCE CRITERION (THE NEWTON-RAPHSON METHOD FOR THE CALULATION OF THE FIRST 20 POSITIVE ROOTS OF FNF(X)).
CO	: CONTAINER SERIAL NUMBER
FNDF(X)	: DERIVATIVE OF FUNCTION FNF(X)
FNF(X)	: FUNCTION Xtan(X)-Bi
FP	: STERILIZING VALUE (min)
FP1,FP2	: STERILIZING VALUES USED IN THE NEWTON-RAPHSON METHOD (min)
HT,HTA	: OVERALL HEAT TRANSFER COEFFICIENT (W/m^2 °K)
INSULTH	: REQUIRED INSULATION THICKNESS (m)
K(CO)	: (1D ARRAY) THERMAL CONDUCTIVITY OF FOOD IN CONTAINER CO (W/m °K)
KINS	: INSULATION THERMAL CONDUCTIVITY
L(J)	: (1D ARRAY) SIZE OF CONTAINER (m) IN THE DIRECTION (J).
LETH(J)	:(1D ARRAY) LETHALITY AT TIME J
LL(CO,I)	: (2D ARRAY) SIZE OF CONTAINER (m)
MEAL$(CO)	: (1D ARRAY) NAME OF MEAL IN CONTAINER
RT(COUNT)	: (1D ARRAY) THE FIRST 20 ROOTS OF THE EQUATION FNF(X)
SD	: DIRECTION (INFINITE SLAB) SERIAL NUMBER
STP	: STEP FOR INITIAL GUESSES (THE NEWTON-RAPHSON METHOD FOR THE CALULATION OF THE FIRST 20 POSITIVE ROOTS OF FNF(X))
TCOOL	: COOLING TIME (min)
TFP(CO)	:(1D ARRAY) TARGET STERILIZING VALUE (m) FOR CONTAINER CO
THEAT	: HEATING TIME (min)
U(M)	:(1D ARRAY) TEMPERATURE AT THE REFERENCE POINT AT TIME M (°C)
W	:UNACCOMPLISHED TEMPERATURE DIFFERENCE CALCULATED ON THE BASIS OF A SINGLE ROOTOF EQUATION FNF(X). (W= (T-Tr)/(Ti-Tr) where Tr,Ti THE RETORT AND INITIAL TEMPERATURE RESPECTIVELY).
WPROD	: UNACCOMPLISHED TEMPERATURE DIFFERENCE BASED ON 3 DIRECTIONS. PRODUCT OF THE WSUM(I).

WSUM (I)	: (ID ARRAY) UNACCOMPLISHED TEMPERATURE DIFFERENCE CALCULATED ON THE BASIS OF THE 20 ROOTS OF EQUATION FNF(X) FOR THE DIRECTION (I).
WSUM	UNACCOMPLISHED TEMPERATURE DIFFERENCE CALCULATED ON THE BASIS OF THE 20ROOTS OF EQUATION FNF(X). (SUM OF W).
X(J)	: (1D ARRAY) DISTANCE OF THE REFERENCE POINT FROM CENTER (m) (DIRECTION J)
XL	: DISTANCE OF THE REFERENCE POINT FROM CENTER (m) (DIRECTION OF LENGTH)
XT	: DISTANCE OF THE REFERENCE POINT FROM CENTER (m) (DIRECTION OF HEIGHT)
XW	: DISTANCE OF THE REFERENCE POINT FROM CENTER (m) (DIRECTION OF WIDTH)
Z(C0)	: (1D ARRAY) Z VALUE FOR THE TARGET MICRORGANISM IN CONTAINER CO

```
10 '******************** ANLYT-H3* ****************************
20 '***ESTIMATION OF THE OVERALL   HEAT TRANSFER COEFFICIENT***********
30 DIM U(4000),R(3,20),RT(20),XRON(4000),UEXPR(4000)
40 PRINT : INPUT "H";HT:HT=190
50 PRINT : INPUT "LENGTH (m)";L(1):L(1)=.06
60 PRINT : INPUT "WIDTH (m)";L(2):L(2)=.035
70 PRINT : INPUT "THICKNESS (m)";L(3):L(3)=.015
80 PRINT : INPUT "THERMAL CONDUCTIVITY K";K:K=.637
85 PRINT: INPUT "THERMAL DIFFUSIVITY=";ALPHA:ALPHA=1.587E-07
90 PRINT "DISTANCE FROM CENTER XL,XW,XT":X(1)=0:X(2)=0:X(3)=0
100 PRINT :INPUT "HEATING TIME";THEAT:THEAT=60
110 PRINT:INPUT "COOLING TIME";TCOOL:TCOOL=20
120 EXPER1$="DATA2.PRN"
130 DH=.5
140 OPEN EXPER1$ FOR INPUT AS #2
150 INPUT #2,N
160 FOR I=1 TO N
170 INPUT #2,XRON(I),UEXPR(I)
180 NEXT I
190 CLOSE #2
200 GOSUB 800
210 GOSUB 3000
220 GOSUB 4000
230 SS1=SS
240 HT=HT+DH
250 GOSUB 800
260 GOSUB 3000
270 GOSUB 4000
280 SS2=SS
290 IF ABS(SS1-SS2)<.5 GOTO 400
300 HT=(HT-DH)-((SS2-SS1)*1)/DH:LPRINT SS1,SS2,HT,TIME$
310 GOTO 200
320 LPRINT "convergence achieved, h=",HT-DH
410 END
800 '****BIOT # FOR THE 3 INFINITE SLABS************
805 FOR SD=1 TO 3
810 BI(SD)=HT*L(SD)/K
820 GOSUB 1000
830 FOR J=1 TO 20
840 R(SD,J)=RT(J)
850 NEXT J
860 NEXT SD
870 RETURN
1000 '*****ESTIMATION OF THE FIRST 6 POSITIVE ROOTS OF THE EQUATION
1010 '******  ATANA=C*****************************************************
1020 CLS
1025 BI=BI(SD)
1030 FOR J=0 TO COUNT
1032 RT(J)=0
1034 NEXT J
1040 DEF FNF(X)=X*TAN(X)-BI
1050 DEF FNDF(X)=TAN(X)+X/(COS(X))^2
1060 COUNT=0
1075 STP=.05
1080 'initial guesses for the roots
1090 FOR J=0 TO 61 STEP STP: X1=J:LOCATE 15,25:PRINT J
1100 'convergence dcriterion
1110 CCRIT=.001
1120 'Newton-Raphson method for the estimationm of the  roots
1130 FOR I=1 TO 200
1140 IF ABS (FNF(X1))<CCRIT GOTO 1210
1145 IF X1=0 THEN GOTO 1310
1150 F1=FNF(X1)
1160 DF1=FNDF(X1)
1170 X1=X1-F1/DF1
1180 NEXT I
```

```
1190 'disregard values that did not converge
1200 IF I=200 GOTO 1310
1210 FOR I=0 TO COUNT
1220 'disregard roots already existing
1221 'if bi=0 keep the root=0
1222 IF X1=0 GOTO 1280
1223 'PREVENT ROOTs<1 FROM BEEING DISPOSED
1225 IF RT(I)=0 AND BI<>0 THEN GOTO 1240
1230 IF INT(X1)=INT(RT(I)) THEN GOTO 1310
1240 NEXT I
1250 ' disregard roots other than the first five
1260 IF X1>61 THEN GOTO 1310
1270 'form an array with the roots r(count)
1280 COUNT=COUNT+1:PRINT COUNT
1290 RT(COUNT)=X1
1300 IF COUNT>19 GOTO 1330
1310 NEXT J
1330 FOR J=1 TO COUNT
1360 NEXT J
1370 RETURN
2000 '******* CALCULATION OF THE UNACCOMPLISHED TEMPERATURE CHANGE ********
2010 '******* FOR EACH DIMENSION                                    ********
2020 '
2030 '
2040 WSUM=O
2045 DEFDBL W
2050 FOR J=1 TO 20
2060 W=2*SIN(R(I,J))*COS(R(I,J)*X(I)/L(I))*EXP(-R(I,J)^2*(ALPHA*T/(L(I))^2)/(R
I,J)+SIN(R(I,J))*COS(R(I,J)))
2080 WSUM=WSUM+W
2085 NEXT J
2090 WSUM(I)=WSUM:PRINT WSUM(I)
  00 RETURN
3000 '******CALCULATION OF CENTRAL TEMPERATURES DURING HEATING AND COOLING***
3370 FOR M=0 TO (THEAT+TCOOL) STEP 1
3372 IF M>THEAT GOTO 3373 ELSE GOTO 3375
3373 T=(M-THEAT)*60:GOTO 3380
3375 T=M*60
3380 FOR I=1 TO 3
3390 GOSUB 2000
3400 NEXT I
3410 WPROD=WSUM(1)*WSUM(2)*WSUM(3):PRINT WPROD
3415 TW=121 :TI=21
3417 IF M>THEAT THEN TW=21:TI=U(THEAT)
3420 U(M)=WPROD*(TI-TW)+TW:PRINT U(M)
3440 NEXT M
3450 EXPER$="ANL.PRN"
3460 'OPEN EXPER$ FOR OUTPUT AS #1
3470 FOR J=1 TO (THEAT+TCOOL)
3480 'PRINT #1,J,U(J)
3485 PRINT J,U(J)
3490 NEXT J
3500 'CLOSE #1
3800 PRINT TIME$
3900 RETURN
4000 '***********CALCULATION OF SUMS OF SQUARES******************************
4010 '
4020 SS=0:SQ=0
4030 FOR J=1 TO THEAT
4040 FOR I=1 TO N
4050 IF ABS(J-XRON(I))<.5 GOTO 4070
4060 NEXT I
4070 'PRINT J,U(J),Xron(I),UEXPR(I)
4080 SQ=(U(J)-UEXPR(I))^2
4090 SS=SS+SQ
4100 NEXT J
4300 RETURN
```

```
10 '******************** ANLYT-F3 *****************************
20 '***ANALYTICAL SOLN OF HEAT CONDUCTION*******************
30 DIM U(4000),R(3,20),RT(20)
40 PRINT : INPUT "H";HT:HT=173
50 PRINT : INPUT "LENGTH (m)";L(1):L(1)=.06
60 PRINT : INPUT "WIDTH (m)";L(2):L(2)=.035
70 PRINT : INPUT "THICKNESS (m)";L(3):L(3)=.015
80 PRINT : INPUT "THERMAL CONDUCTIVITY K";K:K=.637
85 PRINT: INPUT "THERMAL DIFFUSIVITY=";ALPHA:ALPHA=1.587E-07
90 PRINT "DISTANCE FROM CENTER XL,XW,XT":X(1)=0:X(2)=0:X(3)=0
100 PRINT :INPUT "HEATING TIME";THEAT:THEAT=60
110 PRINT:INPUT "COOLING TIME";TCOOL:TCOOL=20
200 GOSUB 800:GOSUB 3000
300 END
445 'SAVE THE OUTPUT IN A DOS FILE
800 '****BIOT # FOR THE 3 INFINITE SLABS************
805 FOR SD=1 TO 3
810 BI(SD)=HT*L(SD)/K
820 GOSUB 1000
830 FOR J=1 TO 20
840 R(SD,J)=RT(J)
850 NEXT J
860 NEXT SD
870 RETURN
1000 '*****ESTIMATION OF THE FIRST 6 POSITIVE ROOTS OF THE EQUATION
1010 '******  ATANA=C*********************************************
1020 CLS
1025 BI=BI(SD)
1030 FOR J=0 TO COUNT
1032 RT(J)=0
1034 NEXT J
1040 DEF FNF(X)=X*TAN(X)-BI
1050 DEF FNDF(X)=TAN(X)+X/(COS(X))^2
1060 COUNT=0
1075 STP=.05
1080 'initial guesses for the roots
1090 FOR J=0 TO 61 STEP STP: X1=J:LOCATE 15,25:PRINT J
1100 'convergence dcriterion
1110 CCRIT=.001
1120 'Newton-Raphson method for the estimationm of the  roots
1130 FOR I=1 TO 200
1140 IF ABS (FNF(X1))<CCRIT GOTO 1210
1145 IF X1=0 THEN GOTO 1310
1150 F1=FNF(X1)
1160 DF1=FNDF(X1)
1170 X1=X1-F1/DF1
1180 NEXT I
1190 'disregard values that did not converge
1200 IF I=200 GOTO 1310
1210 FOR I=0 TO COUNT
1220 'disregard roots already existing
1221 'if bi=0 keep the root=0
1222 IF X1=0 GOTO 1280
1223 'PREVENT ROOTs<1 FROM BEEING DISPOSED
1225 IF RT(I)=0 AND BI<>0 THEN GOTO 1240
1230 IF INT(X1)=INT(RT(I)) THEN GOTO 1310
1240 NEXT I
1250 ' disregard roots other than the first five
1260 IF X1>61 THEN GOTO 1310
1270 'form an array with the roots r(count)
1280 COUNT=COUNT+1:PRINT COUNT
1290 RT(COUNT)=X1
1300 IF COUNT>19 GOTO 1330
1310 NEXT J
1330 FOR J=1 TO COUNT
1360 NEXT J
```

```
1370 RETURN
2000 '******* CALCULATION OF THE UNACCOMPLISHED TEMPERATURE CHANGE*********
2010 '******* FOR EACH DIMENSION                                   *********
2020 '
2030 '
2040 WSUM=0
2045 DEFDBL W
2050 FOR J=1 TO 20
2060 W=2*SIN(R(I,J))*COS(R(I,J)*X(I)/L(I))*EXP(-R(I,J)^2*(ALPHA*T/(L(I))^2))/R(
I,J)+SIN(R(I,J))*COS(R(I,J)))
2080 WSUM=WSUM+W
2085 NEXT J
2090 WSUM(I)=WSUM:PRINT WSUM(I)
2100 RETURN
3000 '******CALCULATION OF CENTRAL TEMPERATURES DURING HEATING AND COOLING***
3370 FOR M=0 TO (THEAT+TCOOL) STEP 1
3372 IF M>THEAT GOTO 3373 ELSE GOTO 3375
3373 T=(M-THEAT)*60:GOTO 3380
3375 T=M*60
3380 FOR I=1 TO 3
3390 GOSUB 2000
3400 NEXT I
3410 WPROD=WSUM(1)*WSUM(2)*WSUM(3):PRINT WPROD
3415 TW=121 :TI=21
3417 IF M>THEAT THEN TW=21:TI=U(THEAT)
3420 U(M)=WPROD*(TI-TW)+TW:PRINT U(M)
3440 NEXT M
3450 EXPER$="ANL.PRN"
3460 OPEN EXPER$ FOR OUTPUT AS #1
3470 FOR J=1 TO (THEAT+TCOOL)
3480 PRINT #1,J,U(J)
3485 PRINT J,U(J)
3490 NEXT J
3500 CLOSE #1
3800 PRINT TIME$
3900 RETURN
```

```
10 '******************** MAIN-PL.BAS*****************************
20 '***PROCESS TIME AND INSULATION THICKNESS CALCULATION (CHAIN TO COST)*******
30 DIM U(4000),RO(3,20),RT(20),LETH(4000),LL(3,3),XX(3,3)
40 PRINT : INPUT "H";HT:HT=168
42 HTA=HT
44  PRINT :INPUT "FIRST ESIMATE OF HEATING TIME";THEAT:THEAT=60
46 PRINT:INPUT "COOLING TIME";TCOOL:TCOOL=20
47 PRINT :INPUT "INULATION THERMAL CONDUCTIVITY W/m K";KINS:KINS=.2 :CO=1
48 IF CO>3 GOTO 140
49 PRINT "CONTAINER" CO: INPUT "MEAL NAME";MEAL$(CO)
50 PRINT : INPUT "LENGTH (m)";LL(CO,1):LL(CO,1)=.06
60 PRINT : INPUT "WIDTH (m)";LL(CO,2):LL(CO,2)=.035
70 PRINT : INPUT "THICKNESS (m)";LL(CO,3):LL(CO,3)=.015
75 IF CO>1 THEN CHAIN "COST.BAS",120,ALL
77 CHAIN "COST.BAS",,ALL
80 PRINT : INPUT "THERMAL CONDUCTIVITY K";K(CO):K(CO)=.637
85 PRINT: INPUT "THERMAL DIFFUSIVITY=";ALPHA(CO):ALPHA(CO)=1.587E-07
90 PRINT "DISTANCE FROM CENTER XL,XW,XT":XX(CO,1)=0:XX(CO,2)=0:XX(CO,3)=0
120 PRINT : INPUT "Z VALUE";Z(CO):Z(CO)=10
125 PRINT : INPUT"THE TARGET STERILIZING VALUE (min)";TFP(CO)
130 CO=CO+1:GOTO 48
140 PRINT "*****************END OF INPUT************************************"
150 FOR CO=1 TO 3
160 GOSUB 400
165 THEAT=20+4*TFP
170 IF CO>1 GOTO 190
180 GOSUB 500:GOTO 200
190 GOSUB 532
200 THEAT(CO)=THEAT
210 THEAT(CO)=THEAT :LPRINT THEAT(CO)
220 NEXT CO
225 'the process time is the longest of the 3 pr.times
  0 IF THEAT(1)>THEAT(2) THEN THEAT=THEAT(1) ELSE THEAT=THEAT(2)
240 IF THEAT>THEAT(3) GOTO 260 ELSE THEAT=THEAT(3)
260 LPRINT: LPRINT THEAT
270 '
275 'calculate the sterilizing value without insulation
280 FOR CO=1 TO 3
290 IF THEAT(CO)=THEAT THEN LPRINT "PROCESS TIME IS BASED ON CONTAINER"CO"CONTAIN
NING"MEAL$(CO) ,"heating,cooling times"THEAT,TCOOL :GOTO 330
297 GOSUB 400:GOSUB 3000:GOSUB 4000
300 LPRINT "fp without insulation"FP
310 IF FP>TFP(CO) AND FP<1.1*TFP(CO) THEN LPRINT "NO INSULATION IS NEEDED FOR CON
NTAINER"CO"CONTAINING" MEAL$(CO):GOTO 330
320 GOSUB 600
325 LPRINT "INSULATION THICKNESS NEEDED FOR CONTAINER"CO"CONTAINING"MEAL$(CO ,IN
SULTH"(m)"
330 NEXT CO
340 END
400 '***************RENAME VARIABLES************************************
405 FOR J=1 TO 3
410 L(J)=LL(CO,J)
420 X(J)=XX(CO,J)
430 NEXT J
440 K=K(CO):ALPHA=ALPHA(CO):Z=Z(CO):TFP=TFP(CO)
450 RETURN
500 '********PROCESS TIME CALCULATION********
530 GOSUB 800
532 GOSUB 3000:GOSUB 4000
540 FP1=0:FP2=0
545 FP1=FP
547 IF ABS(TFP-FP1)<.1 GOTO 598
550 THEAT=THEAT+.1
560 GOSUB 3000: GOSUB 4000
570 FP2=FP
590 THEAT=(THEAT-.1)-((FP1-TFP)/((FP2-FP1)/.1)):LPRINT THEAT,TIME$
```

```
595 GOTO 532
598 LPRINT " THE HEATING AND COOLING TIMES FOR",CO"ARE"THEAT,TCOOL
599 RETURN
600 '******************INSULATION THICKNESS CALCULATION*******************
610 TFP=TFP(CO)
620 HT=35
630 GOSUB 800:GOSUB 3000:GOSUB 4000
640 FP1=0:FP2=0
650 FP1=FP
660 IF ABS(TFP-FP1)<.1 GOTO 720
670 HT=HT+5
680 GOSUB 800:GOSUB 3000:GOSUB 4000
690 FP2=FP
700 HT=(HT-5)-((FP1-TFP)/((FP2-FP1)/5)):LPRINT HT,TIME$
710 GOTO 630
720 INSULTH=((1/HT)-(1/HTA))*KINS
730 HT=HTA
740 RETURN
800 '****BIOT # FOR THE 3 INFINITE SLABS*************
805 FOR SD=1 TO 3
810 BI(SD)=HT*L(SD)/K
820 GOSUB 1000
830 FOR J=1 TO 20
840 RO(SD,J)=RT(J)
850 NEXT J
860 NEXT SD
870 RETURN
1000 '*****ESTIMATION OF THE FIRST 6 POSITIVE ROOTS OF THE EQUATION
1010 '******  ATANA=C*************************************************
1020 CLS
1025 BI=BI(SD)
1030 FOR J=0 TO COUNT
1032 RT(J)=0
1034 NEXT J
1040 DEF FNF(X)=X*TAN(X)-BI
1050 DEF FNDF(X)=TAN(X)+X/(COS(X))^2
1060 COUNT=0
1075 STP=.05
1080 'initial guesses for the roots
1090 FOR J=0 TO 61 STEP STP: X1=J:LOCATE 15,25:PRINT J
1100 'convergence dcriterion
1110 CCRIT=.001
1120 'Newton-Raphson method for the estimationm of the  roots
1130 FOR I=1 TO 200
1140 IF ABS (FNF(X1))<CCRIT GOTO 1210
1145 IF X1=0 THEN GOTO 1310
1150 F1=FNF(X1)
1160 DF1=FNDF(X1)
1170 X1=X1-F1/DF1
1180 NEXT I
1190 'disregard values that did not converge
1200 IF I=200 GOTO 1310
1210 FOR I=0 TO COUNT
1220 'disregard roots already existing
1221 'if bi=0 keep the root=0
1222 IF X1=0 GOTO 1280
1223 'PREVENT ROOTs<1 FROM BEEING DISPOSED
1225 IF RT(I)=0 AND BI<>0 THEN GOTO 1240
1230 IF INT(X1)=INT(RT(I)) THEN GOTO 1310
1240 NEXT I
1250 ' disregard roots other than the first five
1260 IF X1>61 THEN GOTO 1310
1270 'form an array with the roots r(count)
1280 COUNT=COUNT+1:PRINT COUNT
1290 RT(COUNT)=X1
1300 IF COUNT>19 GOTO 1330
```

```
1310 NEXT J
1330 FOR J=1 TO COUNT
1360 NEXT J
1370 RETURN
2000 '******* calculation of the unaccomplished moisture change   *********
2010 '******* for each dimension                                  *********
2020 '
2030 '
2040 WSUM=0
2045 DEFDBL W
2050 FOR J=1 TO 20
2060 W=2*SIN(RO(I,J))*COS(RO(I,J)*X(I)/L(I))*EXP(-RO(I,J)^2*(ALPHA*T/(L(I))^2))/
(RO(I,J)+SIN(RO(I,J))*COS(RO(I,J)))
2080 WSUM=WSUM+W
2085 NEXT J
2090 WSUM(I)=WSUM:PRINT WSUM(I)
2100 RETURN
3000 '******CALCULATION OF CENTRAL TEMPERATUREES DURING HEATING AND COOLING***
3360 COUNT2=0
3370 FOR M=0 TO (THEAT+TCOOL) STEP 1
3372 IF M>THEAT GOTO 3373 ELSE GOTO 3375
3373 T=(M-THEAT)*60:GOTO 3380
3375 T=M*60
3380 FOR I=1 TO 3
3390 GOSUB 2000
3400 NEXT I
3410 WPROD=WSUM(1)*WSUM(2)*WSUM(3):PRINT WPROD
3415 TW=121 :TI=21
3417 IF M>THEAT THEN TW=21:TI=U(THEAT)
3420 U(M)=WPROD*(TI-TW)+TW:PRINT U(M)
3430 COUNT2=COUNT2 + 1
3440 NEXT M
3450 'EXPER$="ANL.PRN"
3460 'OPEN EXPER$ FOR OUTPUT AS #1
3470 'FOR J=1 TO (THEAT+TCOOL)
3480 'PRINT #1,J,U(J)
3485 'PRINT J,U(J)
3490 'NEXT J
3500 'CLOSE #1
3800 PRINT TIME$
3900 RETURN
4000 '
4010 '
4020 SUM=0:FP=0
4030 FOR J=0 TO COUNT2
4040 LETH(J)=10^((U(J)-121.111)/Z)
4050 NEXT J
4060 IF INT(COUNT2/2)=COUNT2/2 THEN COUNT2=COUNT2-1
4070 FOR J=0 TO COUNT2-2 STEP 2
4080 SUM=SUM+1*(LETH(J)+4*LETH(J+1)+LETH(J+2))/3
4090 NEXT J
4100 FP=SUM:LPRINT FP
4200 RETURN
```

APPENDIX B

SAMPLE OF COMPUTER OUTPUT
PREDICTING PROCESS TIME

```
50.22616      08:42:52
7.865225
THE HEATING AND COOLING TIMES FOR          1 ARE 50.22616
20
50.22616
10.73101
10.79969
45.95846      08:47:37
7.481843
7.709377
46.09828      08:50:35
7.732369
THE HEATING AND COOLING TIMES FOR          2 ARE 46.09828
20
46.09828
7.587246
7.64467
33.05965      08:55:04
1.319487
1.338306
26.57935      08:57:28
.2723593
.2769489
22.82388      08:59:34
.0571689
THE HEATING AND COOLING TIMES FOR          3 ARE 22.82388
20
22.82388

50.22616
PROCESS TIME IS BASED ON CONTAINER 1 CONTAININGBEEF     heating.cooling time
50.22616      20
10.73101
f= without insulation 10.73101
3.341709
4.269027
79.51729      09:26:25
7.319173
7.829492
84.22834      09:51:23
7.800938
INSULATION THICKNESS NEEDED FOR CONTAINER 2 CONTAININGRICE
1.164021E-03 (m)
7.647706
f= without insulation 7.647706
.6655295
.9485735
40.00987      10:29:16
.2557978
.4340378
35.63942      10:52:57
.144938
INSULATION THICKNESS NEEDED FOR CONTAINER 3 CONTAININGPEARS
4.421287E-03 (m)
```

APPENDIX C

THERMAL DIFFUSIVITY OF THERMOSTABILIZED FOODS

Appendix C

Thermal Diffusivities of TMT Foods

A. Objective and Motivation

The objectives are to : (1) estimate the thermal diffusivites of TMT foods as a function temperature with the COST program, (2) experimentally measure the thermal diffusivities, and (3) compare the predicted and experimental results. Thermal diffusivities are necessary data for computer simulation of the temperature history of foods.

B. Theoretical Estimation

Thermal properties (such as conductivity ,diffusivity enthalpy, specific heat, and ice fraction) of food samples can be estimated by computer program developed by COST when given the following information:

1. category of the food sample (namely, cereals, milk or eggs, fat or oil, meat, fish, vegetables, nuts, sugars, fruits, beverages, sauces or soups, confectionery, cheese, and miscellaneous);
2. range of water content;
3. compositions of food sample (namely, % water, % protein, % fat, % carbohydrates, % minerals);
4. specific temperature or temperature range of interest;
5. other helpful details such as form of product (solid or liquid), density of liquid portion, density of solid portion, and product homogeneity.

C. Experimental Measurements

A direct method was used to measure the thermal diffusivities of TMT foods. In this experiment, a TMT food sample was filled inside a 211x400 can which had a T-type thermocouple located at the geometrical center. The two ends of the can were sealed with metal lids and then insulated with Styrofoam.

To conduct the experiment, the can was first placed in a water bath at 35 °C until it reached an equilibrium temperature (close to 35 °C). The can was then moved to another water bath at a higher temperature of 45°C, and simultaneously the center temperature of the can was being monitored with a data acquisition system. The

temperature history curve was used to calculate the thermal diffusivity of the food at 40 °C (average temperature of 35° and 45 °).

Similarly, the thermal diffusivities at 60 °C were measured using water baths of 55 °C and 65 °C, and the thermal diffusivities at 80 °C were measured using water baths of 75 °C and 85 °C.

To check the accuracy of this experimental technique, we measured the thermal diffusivity of bentonite solution with this experimental technique. We also measured the thermal conductivity, specific heat capacity, and density with other analytical techniques, and used these values to calculate the thermal diffusivity. The thermal diffusivities obtained from these two methods were within 5 %.

D. Results

Table 3 compares the experimental and theoretical predicted thermal diffusivites of TMT foods. In general, the predicted values are higher than the experimental values. The prediction values increase with temperature, and the experimental values seem to be insensitive to changes in temperature. The food items have quite a narrow range, from 1.3 to 1.5. It is likely that the experimental values are more accurate than the predicted values.

APPENDIX D

THERMAL CONDUCTIVITY OF NAPKIN

Appendix D

Thermal Conductivity of Napkin

A. Objective and Motivation

To measure the thermal conductivity of a commercial restaurant napkin. This information is required by the computer program.

B. Experimental Method

The diagram below shows the setup we used. A napkin was placed between a hot plate and a glass flask. The glass flask had a circular bottom of 6 cm in diameter and contained 200 ml of water.

The thermal conductivity k was determined from the following two equations:

Heat flux: $$\frac{Q}{A} = \frac{m\,C_p\,(T_2 - T_1)}{t\,A}$$

Thermal conductivity: $$\frac{Q}{A} = \frac{k\,(T_p - T_n)}{x}$$

where

Q = amount of heat flow through the napkin which was be determined by measuring the temperature rise of the 200 ml water in 5 minutes, W/sec.

A = heat transfer area, ($0.03^2\pi$ m^2)

m = amount of water being heated (200 ml)

Cp = heat capacity of water (4.181 kJ/kg °C)

T_2 = water temperature after heating, °C

T_1 = water temperature before heating, °C

T_p = temperature of hot plate, °C

T_n = temperature of napkin, °C

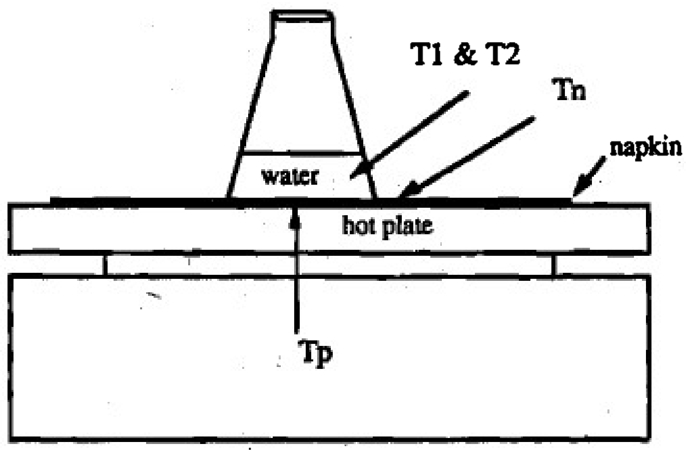
t = heating time, (300 sec)

x = thickness on the upper surface of napkin, m

k = thermal conductivity, W/(m °K)

C. Experimental Results

The average thermal conductivity was found to be a function of the napkin thickness: 0.253 W/(m °K) for 0.8 mm thickness, 0.203 W/(m °K) for 1.6 mm thickness, and 0.146 W/(m °K) for 3 mm thickness. The lower thermal conductivity for thicker napkin might be due to the larger amount of air trapped inside.



Equipment for measuring thermal conductivity of napkin

APPENDIX E

DENSITY OF THERMOSTABILIZED FOODS

Appendix E

Densities of TMT Foods

A. Objective and Motivation

To measure the densities of the TMT food items as a function of temperature. These data are usedto calculate the volume of compartment necessary to contain the required weight of foods.

B. Experimental

A gas stereopycnometer was used to measure the densities of TMT foods.

C. Results

	Density (g/cc)			
	25°C	S.D.	40°C	S.D.
Apple dessert	1.153	0.011	1.129	0.018
Chicken stew	1.107	0.008	1.092	0.014
Chocolate Pudding	1.208	0.010	1.165	0.020
Pork with BBQ sauce	1.142	0.019	1.094	0.016
Potatoes augratin	1.112	0.013	1.086	0.023
Rice with butter sauce	1.273	0.021	1.208	0.034
Sliced peaches	1.143	0.016	1.102	0.017
Tuna noodles	1.075	0.02	1.075	0.016

APPENDIX F

TECHNICAL REPORT
ON
A SIMPLE METHOD FOR MEASURING THERMAL DIFFUSIVITY
OF HOMOGENEOUS AND NONHOMOGENEOUS FOODS

A Simple Method for Measuring Thermal Diffusivities of Homogeneous and Nonhomogeneous Foods

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Running Head: Method for measuring thermal diffusivity

ABSTRACT

A unsteady state heat conduction method was used to measure thermal diffusivities of both homogeneous and nonhomogeneous foods. The method was verified by measuring thermal diffusivities of 10% bentonite and apple sauce, and the results were found to have reasonably good agreement with the literature values. It was used to measure the thermal diffusivities of eight commercial foods. The data were found to be 1.20 - 1.56 x 10^{-7} m^2/sec between 40°C and 80°C. They were almost insensitive to temperature variations, and had slightly lower values compared to the predictions from a program developed by COST. The method may be used to measure the thermal diffusivities of nonhomogeneous viscous foods.

INTRODUCTION

Thermophysical properties of food such as thermal diffusivity, thermal conductivity, density, and specific heat are important in the design and analysis of food processes. Thermal diffusivity and thermal conductivity are related by the equation:

$$\alpha = \frac{k}{\rho\, c_p} \qquad (1)$$

There are two general approaches to measure thermal diffusivity. The first approach is to experimentally determine k, ρ, and c_p, and then calculate α. The second approach is simply to measure thermal diffusivity directly. Methods to determine thermal diffusivity and thermal conductivity have been reviewed by Singh (1982). Dickerson et al. was the first group to design an apparatus for direct measurement of thermal diffusivity (1965). In their experiments, both the center and the surface temperatures of the thermal diffusivity apparatus were monitored at constant heating rates. Instruments were required to produce ramp function change on temperature of surrounding medium. Bhowmik & Hayakawa (1979) used a similar apparatus, but they imposed instead a step function change on temperature, and used the heat conduction solution for an infinite cylinder as well as the f values to determine thermal diffusivities. Uno & Hayakawa (1980) derived an analytical solution for heat conduction in a finite cylinder by assuming that the surface heat transfer conductances at its top, bottom and side surfaces were all finite and different from each other. Hayakawa et al. (1983) developed another procedure through analysis of transient heat conduction formula to determine the thermal diffusivity of some spherical, homogeneous sample such as fresh tomatoes and potatoes. The methods developed by these researchers either required sophisticated apparatus or extensive computer calculations, and were intended for measuring the thermal diffusivities of homogeneous samples.

Thermal conductivity of homogeneous food is often measured with the probe method (Reidy et al., 1951, Mohsenin, 1980). For nonhomogeneous foods, it is necessary to make measurements at many different locations in the food sample to obtain a representative value, because the results are location dependent. This situation may be improved by first measuring a representative α (as was done in this study), ρ, and c_p and then calculating the thermal conductivity k from these three parameters.

Since most commercial foods are nonhomogeneous, there is a need for a simple method to measure their thermophysical properties. The objectives of this work were (1) to investigate if a simple method can be used to measure the thermal diffusivities of nonhomogeneous foods, and (2) to study the thermophysical properties of several commercial foods. The simple method has the advantages that the apparatus used in the experiments are inexpensive and readily available. It requires only about 300 gram food samples to obtain a representative thermal diffusivity.

MATERIALS AND METHODS

Materials

The experimental method for thermal diffusivity measurements was verified with a ten weight percent aqueous bentonite paste (purified grade powder from Fisher Scientific Co.) and apple sauce (Foodtown brand, purchased from a local supermarket). Thermal diffusivities and thermal conductivities of those materials were readily available in the literature, and were used for comparing to the experimental values.

Thermal diffusivities of eight kinds of food samples provided by US Army Natick RD&E Center were also determined. The samples were apple dessert, chicken stew, chocolate pudding, pork in barbecue sauce, potatoes Au-Gratin, rice in butter sauce, sliced peaches, and tuna with noodles. These samples are nonhomogeneous, except for chocolate pudding. The compositions are given in Table 1.

Procedures

The food samples were first well mixed with an electric blender before density and specific heat measurements were conducted. Since most of the foods were nonhomogeneous, this step made them more homogeneous and yielded more representative measurements.

Density measurements

The bulk density of samples were determined by a gas stereopycnometer (Quantachrome Model SPY-2). The experiments was repeated two times for each samples. The reported datum was a mean of the two measurements.

Specific heat measurements

The specific heat of samples were determined by a differential scanning calorimeter (Mettler Model TA 4000 system). The temperatures ranged from 0 to 90°C with a constant heating rate of 5°C/min. The specific heat measurement was conducted twice for each samples and the reported data were the means.

Thermal diffusivity measurements

Cylindrical cans (211 x400) were used in our experiments. The experimental setup was shown in Fig.1. Each can was filled with sample without headspace, and a lid with a 2-inch T-type (copper-constantan) thermocouple at the center was placed on the can. Both ends of the can were insulated by styrofoam with a plastic cover for limiting heat transfer in the radial direction only. A silicone sealant was used to prevent water leakage from the ends of apparatus during heating. The filled can was then placed in a constant, preset temperature water bath with an isotemp immersion circulator (Fisher Scientific Co., Model No. 730) and held for sufficient time (about 2 hours) to insure that the sample attained a uniform constant temperature throughout its whole mass. The preheated can was then transferred quickly to another constant temperature water bath at a higher temperature than the previous one and a data acquisition system was initiated simultaneously to record the temperature of food during heating. For determining thermal diffusivity of foods at 40°C, the first and second water bath temperatures were set at 35°C and 45°C, respectively. Similar procedures were used to obtain the thermal diffusivity data at higher temperatures of 60°C and 80°C. The experiment was repeated three times for each can per temperature. The experiment was also repeated two times on the same sample in a different can. Each datum was a mean of six repeated experiments, with one standard deviation.

For unsteady heat conduction in an infinite cylinder with constant thermal diffusivity (Bird et al., 1960):

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] \quad (2)$$

where $\alpha = \dfrac{k}{\rho c_p}$

Assumptions for this study were: (1) homogeneous & isotropic sample, (2) infinite cylindrical shape of canned food, (3) step-function temperature change of heat exchange medium, and (4) no heat transfer from both ends of the can.

The boundary conditions are:

$T = T_i,\ 0 \leq r \leq R,\ t = 0$

$T = T_s,\ r = R,\ t > 0$

$\frac{\partial T}{\partial r} = 0,\ r = 0$

The analytical solution of temperature profiles for an infinite cylinder was (Carslaw and Jaeger, 1959):

$$\frac{T_s - T}{T_s - T_i} = \sum_{n=1}^{\infty} \frac{2}{\mu_n J_1(\mu_n)} \exp(-\mu_n^2 F_o) J_o(\mu_n \frac{r}{R}) \qquad (3)$$

where $F_o = \frac{\alpha t}{R^2}$

and the center temperatures can be approximated by the equation (when $F_o > 0.1$):

$$\ln \frac{T_s - T}{T_s - T_i} = \text{constant} - [(2.4048)^2 \frac{\alpha}{R^2}]\, t \qquad (4)$$

From the plot of $\ln \frac{T_s - T}{T_s - T_i}$ versus time, α can be obtained from the slope of the linear portion of the curve by performing linear regression:

$$\alpha = -\ \frac{\text{slope x } R^2}{5.783} \qquad (5)$$

where α and R had dimensions of m and m^2/sec, respectively.

RESULTS AND DISCUSSION

Verification of experimental method

A typical example of the temperature history curve for heat penetration (10% bentonite at 40°C) was shown in Fig. 2. From it, the slope of the linear portion was -8.963 x 10^{-4} /sec. The average of several inside diameter measurements of the can was 0.066 m. From Eqn. 5, we obtained

$$\alpha = -\frac{8.963 \times 10^{-4} \times (0.033)^2}{5.783}$$

$$= 1.688 \times 10^{-7}\ m^2/sec$$

To verify our experimental method, we measured the thermal diffusivities for two homogeneous samples, 10% bentonite paste and apple sauce (Table 2). The thermal diffusivity of 10% bentonite varied between 1.65 - 1.57 x 10^{-7} m^2/sec at temperature range of 40 to 80°C. These results compared well to the literature values: 1.87 x 10^{-7} m^2/sec for 9% bentonite suspension (Hayakawa et al., 1974), 1.75 x 10^{-7} m^2/sec for 8% bentonite suspension (Uno et al., 1980), and 1.51 x 10^{-7} m^2/sec for 10% bentonite suspension (Niekamp et al., 1984). For apple sauce, the thermal diffusivity varied between 1.44 - 1.33 x 10^{-7} m^2/sec at temperature range of 40 to 80°C. These results also compared well to the value 1.61 x 10^{-7} m^2/sec of Uno et al. (1980). The slight differences in the above thermal diffusivity values may be due to the different methods and conditions used in the experiments.

To further verify our experimental method, we also measured thermal conductivities (by direct probe method), densities, and specific heat of the 10% bentonite and apple sauce. These values were used to calculate the thermal diffusivities with Eqn. 1. The calculated values compared quite well to the experimental values, with less than 10% difference (Table 2). The consistency suggested that our method was rather reliable. The results showed that even though the length to radius ratio of the cans used in these experiments was only two, the infinite cylinder assumption was still valid due to the heat insulations at the two ends.

Thermophysical properties measurements of foods

Another objective of this work was to examine the thermal properties of real foods since these kinds of data were rare in the literature. The thermal diffusivities of eight kinds of commercial foods were measured (Table 3). The method could measure the thermal diffusivities of most samples, except sliced peaches which were not a good heat conduction model. The experimental thermal diffusivities and thermal conductivities of the foods were in the range of 1.20 - 1.56 x 10^{-7} m^2/sec and 0.44 - 0.67 W/mK, respectively, between temperatures of 40°C and 80°C.

A computer program developed by the subcommittee of COST 90 was also used here to predict the thermal properties of foods, and the predicted values were shown in Table 3. The predicted thermal diffusivities were higher than those obtained from the experiments, except for sliced peaches. The program predicted that thermal diffusivity should increase with temperature; however, the experimental values were relatively insensitive to temperature variations. The discrepancy may be due to the presence of void space in the nonhomogeneous foods. The expansion of the entrapped air in void space could reduce the heat conduction rate in food materials during heating.

The effect of food homogeneity on the thermal diffusivity was also investigated using both non-blended and blended samples. The blended samples of chicken stew and sliced peaches were prepared by mixing the food samples in a household blender for 3 minutes. In Table 4, the thermal diffusivities of the blended samples (1.43 - 1.34 x 10^{-7} m^2/sec) were about 4% higher than those of non-blended samples (1.38 - 1.27 x 10^{-7} m^2/sec) for chicken stew. This suggested that the method may also be used to measure thermal diffusivities for some nonhomogeneous food samples.

We were unable to obtain reliable thermal diffusivities for non-blended sliced peaches at 60°C and 80°C. Although the heating curve for 40°C still showed a linear portion, the same was not observed for 80°C (Fig. 3). It suggested that the non-blended sliced peaches no longer followed the heat conduction mechanism at 80°C, and convective heat transfer might have occurred. To the contrary, the thermal diffusivities of the blended sliced peaches could be measured at 80°C. The thermal diffusivities of the blended samples were found to be slightly lower than those of the non-blended samples (Table 4). These observations suggested that the blending of sliced peaches tended to increase the viscosity of the whole mass and result in the food behaving more like a heat conduction food model.

CONCLUSION

The simple method described in this work was able to measure the thermal diffusivities of both nonhomogeneous and homogeneous foods with reasonable results. The thermal diffusivities and thermal conductivities of the foods examined were found in the range of 1.20 - 1.56 x 10^{-7} m^2/sec and 0.44 - 0.67 W/mK, respectively, between temperatures of 40°C and 80°C. The thermal diffusivities were almost insensitive to temperature variations, and have slightly lower values compared to predictions from the COST program. The thermal diffusivities obtained for blended chicken stew samples were slightly higher than those for non-blended samples.

NOMENCLATURE

Symbol

c_p Specific heat, kJ/kgK

F_o Fouier number, dimensionless process time

J_o Bessel function of first kind of order zero

J_1 Bessel function of first kind of order one

k Thermal conductivity, W/mK

R Radius, m

r Radial coordinate

T_s Temperature of surrounding medium, °C

T_i Initial temperature, °C

t Time, sec

Greek letters

α Thermal diffusivity, m^2/sec

μ_n Roots of Bessel function $J_0(\mu_n)$

ρ Density, kg/m^3

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Table 1. Compositions of food samples [a]

Samples/Components [b]	Water	Carbohydrates	Fat	Protein	Ash
Apple Dessert (AD)	72.9	25.7	0.9	0.3	0.2
Chocolate Pudding (CP)	54.2	41.2	2.0	1.5	1.1
Chicken Stew (CS)	76.8	7.6	5.0	9.3	1.3
Potatoes Au-Gratin (PA)	76.2	15.0	4.3	3.0	1.5
Pork in BBQ sauce (PB)	63.3	7.6	11.1	16.6	1.4
Rice in Butter sauce (RB)	65.2	26.4	5.0	2.5	0.9
Sliced Peaches (SP)	81.2	18.0	0.1	0.5	0.2
Tuna with Noodles (TN)	72.8	13.3	3.6	10.3	0.0

[a] Compositions provided by US Army Natick RD&E Center
[b] Composition % (w/w)

Table 2. Experimental thermal diffusivities of 10% bentonite and apple sauce

Samples	Temp [a]	α(exp) [b]	α(exp) [c]
10% bentonite	40	1.650	1.556 *
	60	1.599	1.554 *
	80	1.569	1.542 *
apple sauce	40	1.437	1.527
	60	1.386	1.513
	80	1.333	1.498

a Temperature (°C)

b Experimental thermal diffusivity ($\times 10^{-7}$ m^2/sec) with standard deviation less than 3%

c Thermal diffusivity calculated from k, ρ, and c_p ($\times 10^{-7}$ m^2/sec) (Sheen et al., 1991)

* Data shown was 7.5% bentonite (these values should be slightly higher at 10% bentonite, Niekamp et al., 1984)

Table 3. Experimental thermal physical properties of food samples

Samples	Temp [a]	α(exp) [b]	ρ(exp) [c]	c_p(exp) [d]	k (cal) [e]	α(pred) [f]	k(pred) [g]
AD	40	1.340 ± 0.013	1128.8	3.635	0.550	1.464	0.546
	60	1.350 ± 0.049		3.625	0.552	1.543	0.574
	80	1.342 ± 0.052		3.745	0.567	1.622	0.600
CP	40	1.317 ± 0.051	1165.0	3.290	0.505	1.441	0.478
	60	1.284 ± 0.034		3.285	0.491	1.511	0.499
	80	1.233 ± 0.046		3.380	0.486	1.582	0.521
CS	40	1.384 ± 0.043	1091.5	3.525	0.532	1.430	0.544
	60	1.345 ± 0.028		3.565	0.523	1.508	0.571
	80	1.273 ± 0.026		3.595	0.499	1.588	0.599
PA	40	1.420 ± 0.034	1086.1	3.695	0.570	1.451	0.548
	60	1.366 ± 0.029		3.645	0.541	1.530	0.575
	80	1.348 ± 0.030		3.660	0.536	1.610	0.602
PB	40	1.266 ± 0.026	1039.9	3.240	0.449	1.378	0.488
	60	1.245 ± 0.025		3.230	0.440	1.449	0.511
	80	1.202 ± 0.023		3.380	0.444	1.521	0.534
RB	40	1.373 ± 0.033	1208.1	3.050	0.506	1.441	0.513
	60	1.376 ± 0.040		3.200	0.532	1.516	0.538
	80	1.442 ± 0.098		3.245	0.557	1.591	0.562
TN	40	1.418 ± 0.028	1075.0	3.645	0.556	1.426	0.533
	60	1.405 ± 0.034		3.740	0.565	1.503	0.559
	80	1.385 ± 0.038		3.800	0.566	1.580	0.585
SP *	40	1.545 ± 0.074	1105.5	3.801	0.647	1.470	0.572
	60	1.523 ± 0.083		3.815	0.640	1.552	0.601
	80	1.558 ± 0.072		3.915	0.672	1.635	0.680

a Temperature (°C)
b Experimental thermal diffusivity with standard deviation ($\times 10^{-7}$ m^2/sec)
c Experimental density (kg/m^3), varies very slightly within 40 to 80°C
d Experimental specific heat (kJ/kgK)
e Thermal conductivity calculated from α, ρ, and c_p (W/mK)
f Thermal diffusivity predicted by COST program ($\times 10^{-7}$ m^2/sec)
g Thermal conductivity predicted by COST program (W/mK)
* Blended samples used

Table 4. Effect of food homogeneity on thermal diffusivity of chicken stew and sliced peaches

Samples	Temp [a]	α(exp) [b]	α(pred) [c]	α(exp)/α(pred) [d]
CS	40	1.384 ± 0.043	1.430	0.968
	60	1.345 ± 0.028	1.508	0.892
	80	1.273 ± 0.026	1.588	0.802
CS (blended)	40	1.434 ± 0.033	1.430	1.000
	60	1.391 ± 0.041	1.508	0.922
	80	1.338 ± 0.038	1.588	0.843
SP	40	1.644 ± 0.088	1.470	1.118
	60	ND *	1.552	ND *
	80	ND *	1.635	ND *
SP (blended)	40	1.545 ± 0.074	1.470	1.051
	60	1.523 ± 0.083	1.552	0.981
	80	1.558 ± 0.072	1.635	0.953

a Temperature (°C)
b Experimental thermal diffusivity with standard deviation ($\times 10^{-7}$ m^2/sec)
c Thermal diffusivity predicted by COST program ($\times 10^{-7}$ m^2/sec)
d Ratio of experimental and predicted thermal diffusivity
* ND = not determined

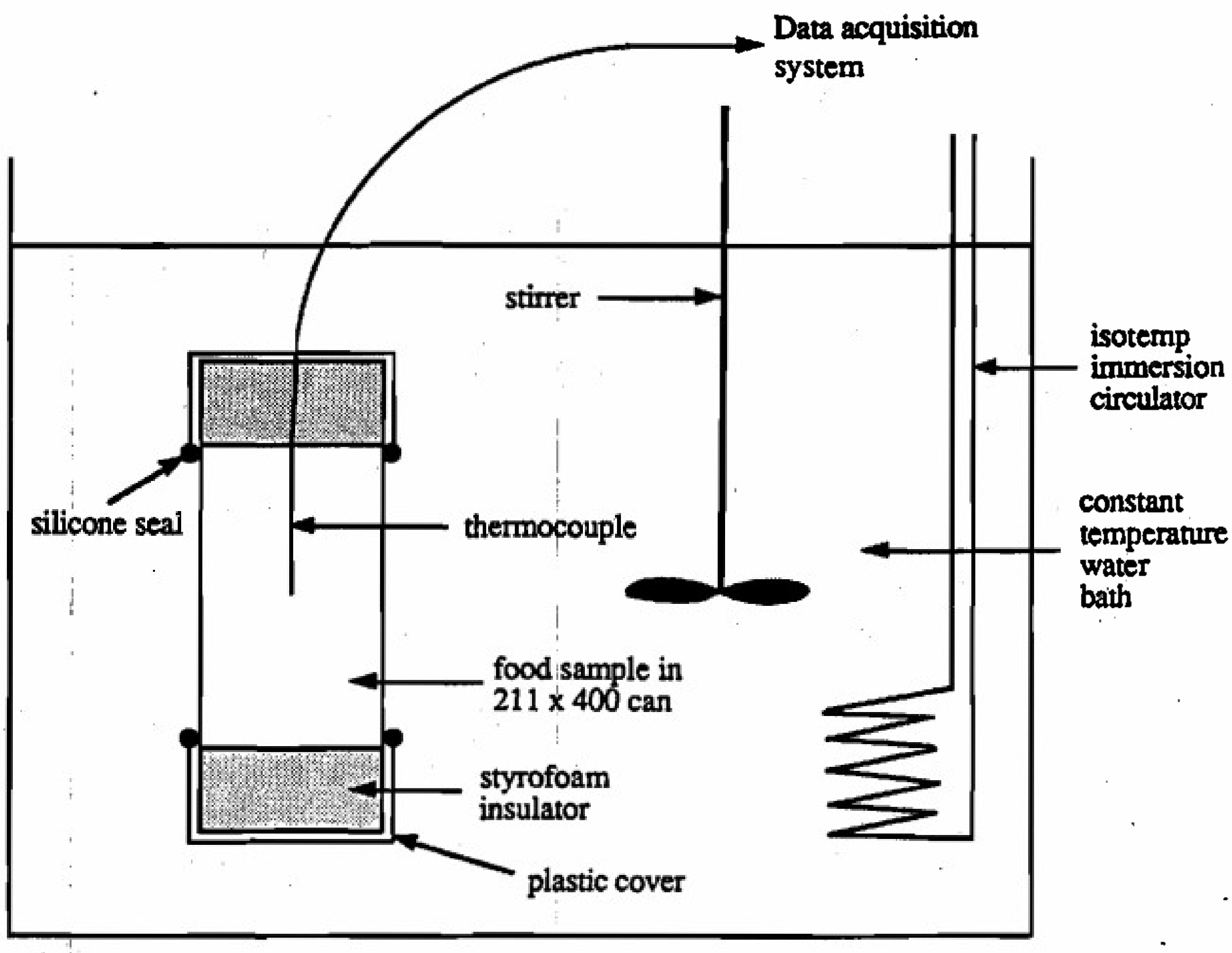


Fig. 1. Experimental setup for thermal diffusivity measurements.

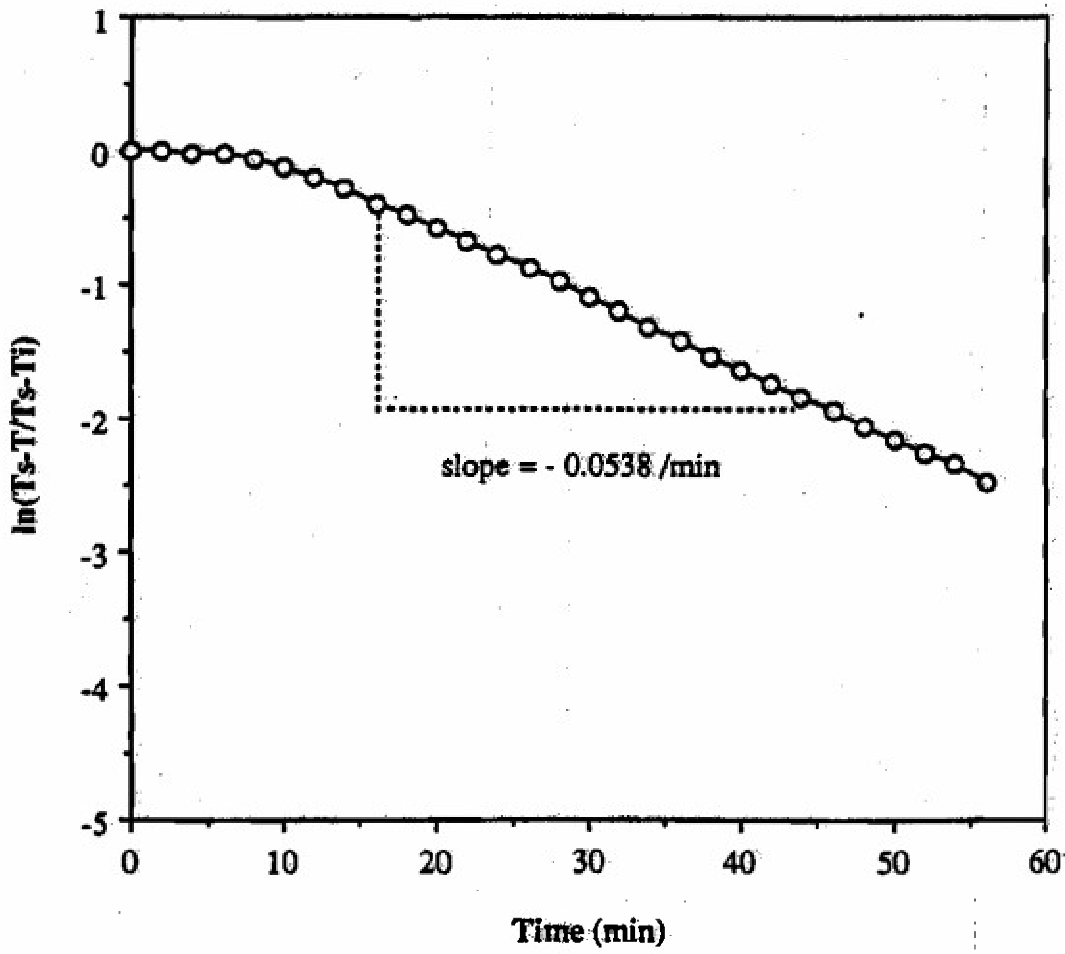


Fig. 2. Typical temperature curve for heat penetration of 10% bentonite paste at 40°C.

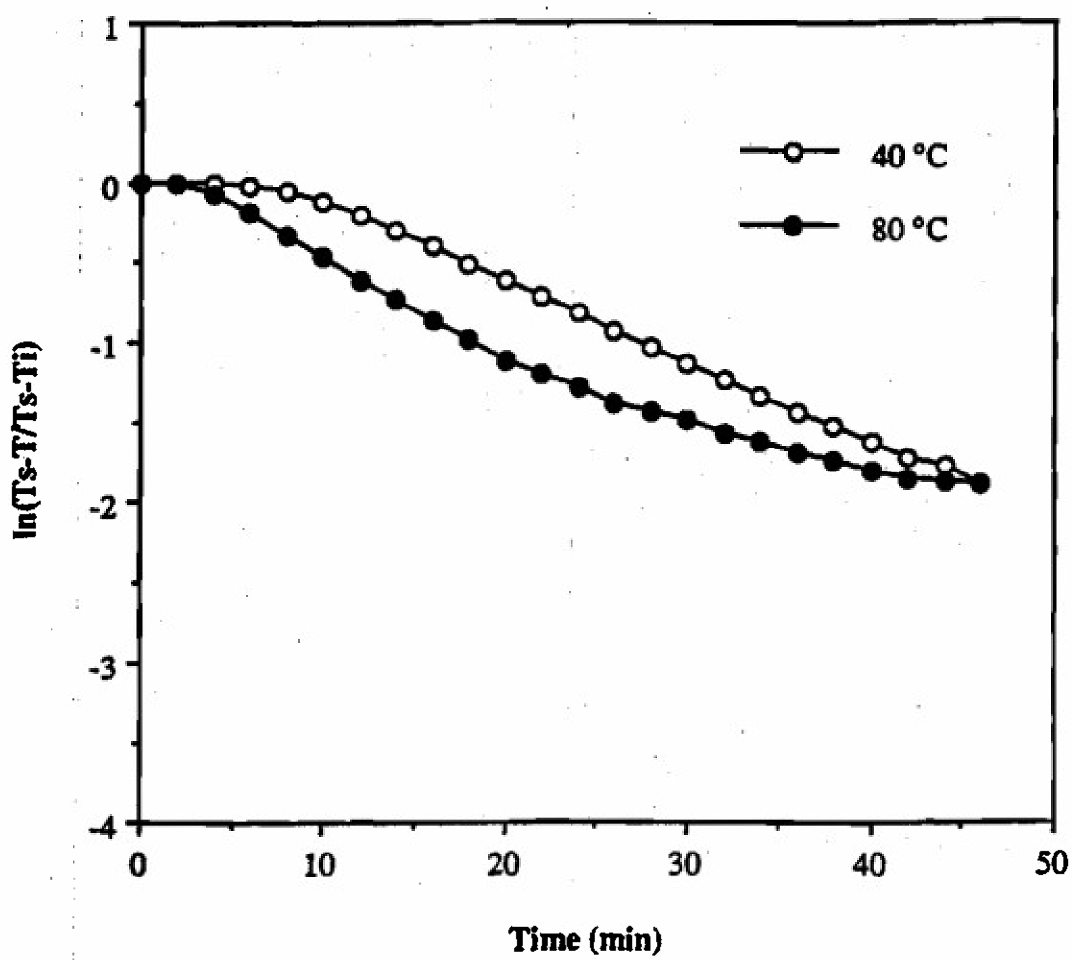
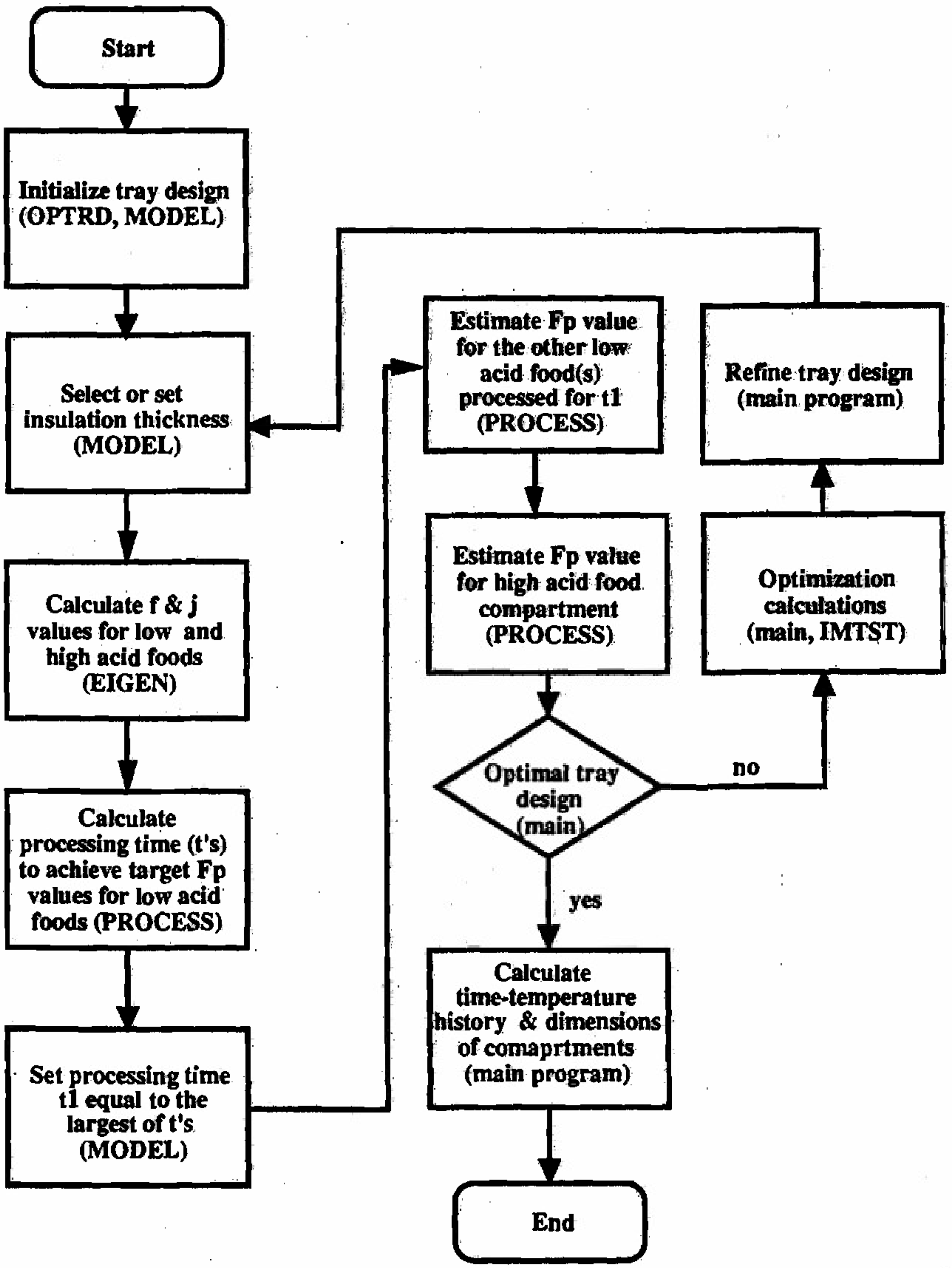


Fig. 3. Temperature curves for heat penetration of non-blended sliced peaches at 40°C and 80°C.

APPENDIX G

COMPUTER PROGRAM



Flow chart using the (f & j) formula method to optimize the compartment tray design (*Capitals in parentheses represent subroutines in the computer program)

Input files required for optimizing compartment tray design

1. "TRAYDESI1.DAT" for specifying the geometric, operating, or safety constraints in optimal compartment tray design;

2. "OPT2.DAT" for specifying the retort conditions and types, volumes, and properties of foods in the tray for optimizatio

Input file for specifying information regarding retort and foods in the menu

1. The actual input file called "TRAYDESI1.DAT" is as follows:

```
0.008
360.6    20.0    0.12983
121.1    25.0    20.0
Chix br
0.000375  0.00    0.00    0.00
0.4561  1.752E-07
10.0    121.1    6.1
Potatoa
0.000261  0.00    0.00    0.00
0.6588  1.387E-07
10.0    121.1    6.1
Grn pea
0.000261  0.00    0.00    0.00
0.4917  1.833E-07
10.0    121.1    6.1
```

2. Explanation of terms for the above input file:

0.008	- G, width of the gap (connecting portion) between compartments in m
360.6	- HTA, overall heat transfer coefficient in $\frac{W}{(m^2 K)}$
20.0	- TCOOL, cooling water temperature in °C.
0.12983	- XKINS, thermal conductivity of insulation material (e.g., napkin) in $\frac{W}{(m K)}$
121.1	- TR, retort temperature in °C.
25.0	- TI, initial food temperature in °C.
20.0	- TC, cooling water temperature in °C.
Chix br	- chix br/grvy, the "entree" food

0.000375	- V(1), the volume for entree compartment in m^3, considering headspace and tapering angle of tray
0	- XX(1,J), where J = 1, 2, or 3, initial value for valuables in optimization calculations
0.4571	- XK(1), thermal conductivity for chix br/grvy, in $\frac{W}{(m\ K)}$
1.752E-07	- ALPHA(1), thermal diffusivity for chix br/grvy in $\frac{m^2}{s}$
10.0	- ZZ(1), z value for "entree" food, in °C.
121.1	- TREF(1), reference temperature in °C. for lethality calculation for "entree" food
6.1	- FP(1), target sterilization lethality F in minutes for "entree" food
Potatoa	- potato augratin, the "starch" food
0.000261	- V(2), the volume for entree compartment in m^3, considering headspace and tapering angle of tray
0	- XX(2,J), where J = 1, 2, or 3, initial value for valuables in optimization calculations
0.6580	- XK(2), thermal conductivity for potato augratin, in $\frac{W}{(m\ K)}$
1.387E-07	- ALPHA(2), thermal diffusivity for potato augratin in $\frac{m^2}{s}$
10.0	- ZZ(12), z value for "starch" food, in °C.
121.1	- TREF(2), reference temperature in °C. for lethality calculation for "starch" food
6.1	- FP(2), target sterilization lethality F in minutes for "starch" food
Grn pea	- green peas, the "vegetable (dessert)" food
0.000261	- V(3), the volume for entree compartment in m^3, considering headspace and tapering angle of tray
0	- XX(3,J), where J = 1, 2, or 3, initial value for valuables in optimization calculations
0.4917	- XK(3), thermal conductivity for green peas, in $\frac{W}{(m\ K)}$
1.833E-07	- ALPHA(3), thermal diffusivity for green peas in $\frac{m^2}{s}$
10.0	- ZZ(3), z value for "entree" food, in °C.
121.1	- TREF(3), reference temperature in °C. for lethality calculation for "vegetable" food; for high acid dessert TREF(3) was chosen as 100.0
6.1	- FP(3), target sterilization lethality F in minutes for "vegetable" food FP(3) was chosen as 3.1 or high acid dessert.

3. Note:

When a high acid dessert is included in the meal and less lethality is required for the dessert compartment "TRAYDES11.DAT" file should be modified. e.g. for meal 3, it looks this (with target lethality chosen to be 3.1 at refe temperature 100 °C for the dessert— pears slices):

121.1 25.0 20.0

Chicken

0.000375 0.00 0.00 0.00

0.4284 1.429E-07

10.0 121.1 6.1

Chocola

0.000261 0.00 0.00 0.00

0.5291 1.235E-07

10.0 121.1 6.1

Pears

0.000261 0.00 0.00 0.00

0.4501 1.476E-07

10.0 100.0 3.1

Example of output file - Optimization calculation for menu # 12

(I. Intermediate and final results of optimization calculations:) .

TRAY DESIGN OF MULTICOMPARTMENT M.R.E.

MEAL NAMES ARE Chix br Potatoa Grn pea

INDEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
INSUL	0.00000E+00	0.00000E+00	0.00000E+00
HEIGT	2.30000E-02	3.00000E-02	2.90000E-02
LEN	1.50000E-01	2.90000E-01	2.50000E-01

DEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
VDO	0.00000E+00	1.00000E+00	3.29087E-04
WSC	8.00000E-02	1.50000E-01	1.00813E-01
DDSRT	1.50000E-02	3.00000E-02	2.90000E-02
HTIME	1.00000E+01	2.00000E+02	3.58375E+01
FE	6.00000E+00	2.50000E+01	1.30976E+01
FS	6.00000E+00	2.00000E+01	6.16291E+00
FD	1.00000E+00	3.10000E+03	1.32811E+01
TFIN	6.10000E+01	1.21100E+02	1.20818E+02

OBJECTIVE FUNCTION

NAME VALUE REL DEV ABS DEV

DEVIA 1.42416E+01 1.00000E-02 1.00000E-01

ITERATION 0

VARIABLES IN SIMPLEX (CENTROID IS VERTEX 7)

VERTEX	1	2	3	4	5	6	7
INSUL	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00
HEIGT	2.90000E-02	2.48250E-02	2.79131E-02	2.72095E-02	2.31119E-02	2.52976E-02	2.62262E-02
LEN	2.50000E-01	2.57277E-01	2.04918E-01	2.75493E-01	2.32186E-01	2.11903E-01	2.38629E-01
VDO	3.29087E-04	3.44187E-04	3.32464E-04	3.34835E-04	3.52515E-04	3.42150E-04	
WSC	1.00813E-01	1.11238E-01	1.20971E-01	1.04834E-01	1.36070E-01	1.32661E-01	
DDSRT	2.90000E-02	2.48250E-02	2.79131E-02	2.72095E-02	2.31119E-02	2.52976E-02	
HTIME	3.58375E+01	2.86355E+01	3.37466E+01	3.25850E+01	2.56152E+01	2.93324E+01	
FE	1.30976E+01	1.18141E+01	1.21419E+01	1.24124E+01	1.09755E+01	1.15537E+01	
FS	6.16291E+00	6.14307E+00	6.03100E+00	6.04372E+00	6.03057E+00	6.09024E+00	
FD	1.32811E+01	1.20523E+01	1.28050E+01	1.26327E+01	1.13711E+01	1.21223E+01	
TFIN	1.20818E+02	1.20946E+02	1.20845E+02	1.20869E+02	1.20987E+02	1.20930E+02	
DEVIA	1.42416E+01	1.17095E+01	1.28160E+01	1.29014E+01	1.02160E+01	1.14857E+01	

TRAY DESIGN OF MULTICOMPARTMENT M.R.E.

PROCEDURE HAS CONVERGED IN 9 ITERATIONS.

THE SOLUTION IS AS FOLLOWS:

INDEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
INSUL	0.00000E+00	0.00000E+00	0.00000E+00
HEIGT	2.30000E-02	3.00000E-02	2.31119E-02
LEN	1.50000E-01	2.90000E-01	2.32186E-01

DEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
VDO	0.00000E+00	1.00000E+00	3.52515E-04
WSC	8.00000E-02	1.50000E-01	1.36070E-01
DDSRT	1.50000E-02	3.00000E-02	2.31119E-02
HTIME	1.00000E+01	2.00000E+02	2.56152E+01
FE	6.00000E+00	2.50000E+01	1.09755E+01
FS	6.00000E+00	2.00000E+01	6.03057E+00
FD	1.00000E+00	3.10000E+03	1.13711E+01
TFIN	6.10000E+01	1.21100E+02	1.20987E+02

OBJECTIVE FUNCTION

NAME	VALUE	REL DEV	ABS DEV
DEVIA	1.02160E+01	1.00000E-02	1.00000E-01

(2. Time-temperature history of foods:)

AT TIME = min.   TEMP. = DEG. C.

(Time-temperature history for food in entree compartment:)

TIME	TEMP °C. (FOOD)
1.025	27.870
2.049	35.942
21.517	120.667
22.541	120.776
23.566	120.858
24.591	120.919
25.615	120.965
25.615	120.965
25.808	120.738
26.218	118.771
26.751	113.415
27.283	105.425
27.694	97.957
27.886	94.182
30.157	94.182
30.365	89.943
30.806	81.709
31.378	72.454
31.951	64.588
32.392	59.339
32.599	57.091

(Time-temperature history for food in starch compartment:)

1.025	26.500
2.049	30.853
3.074	37.636
4.098	46.228
5.123	55.904
6.148	65.942
7.172	75.706
8.197	84.523

CONTINUE

CONTINUE

9.221	91.377
10.246	96.946
11.271	101.472
12.295	105.150
13.320	108.138
14.345	110.567
15.369	112.541
16.394	114.145
17.418	115.448
18.443	116.507
19.468	117.368
20.492	118.067
21.517	118.635
22.541	119.097
23.566	119.472
24.591	119.777
25.615	120.025
25.615	120.025
25.885	119.801
26.461	117.852
27.207	112.546
27.953	104.630
28.529	97.232
28.799	93.492
31.983	93.492
32.273	89.292
32.892	81.135
33.694	71.966
34.497	64.173
35.115	58.973
35.406	56.746

(Time-temperature history for food in dessert cmpt)

1.025	28.020
2.049	36.486
3.074	48.811
4.098	62.931
5.123	76.879

6.148	88.578
7.172	96.960
8.197	103.182
9.221	107.800
10.246	111.228
11.271	113.772
12.295	115.661
13.320	117.063
14.345	118.103
15.369	118.875
16.394	119.449
17.418	119.874
18.443	120.190
19.468	120.425
20.492	120.599
21.517	120.728
22.541	120.824
23.566	120.895
24.591	120.948
25.615	120.987
25.615	120.987
25.803	120.760
26.204	118.793
26.723	113.436
27.243	105.444
27.644	97.974
27.832	94.198
30.048	94.198
30.250	89.958
30.681	81.723
31.240	72.466
31.798	64.597
32.229	59.348
32.431	57.099

(Optimal tray dimensions:)

ENTREE COMPARTMENT DIMENSION 0.2430115 9.0227351E-02 2.3111865E-02

STARCH COMPARTMENT DIMENSION 0.1175058 0.1298719 2.3111865E-02

DESSERT COMPARTMENT DIMENSION 0.1175058 . 0.1298719 2.3111865E-02

DIMENSION OF INNER DESSERT TRAY 0.1175058 0.1298719 2.3111865E-02

VOLUME OF (OUTER) DESSERT COMPARTMENT 3.5270315E-04

STOP

```
C
C       Main program for
C       the optimization of retortable plastic compartment tray design
C       Ref.: Saguy, I., 1983. Optimization of dynamic systems utilizing the
C       Maximum principle. pp. 321-359. in "Computer-Aided Techniques
C       in Food Technology", ed. I. Saguy, Marcel Dekker, Inc., New York.
C
C *************************** NOMENCLATURE ********************************
C       F objective function
C       X(1),..., X(NX) an array containing values of the independent variables
C       Y(1),..., Y(NY) an array containing values of the dependent variables
C       P(1),..., P(NP) an array conatining values of the parameters in the
C               model which may be varied from one optimization run
C               to the next
C       NX number of independent decision variables
C       NY number of dependent variables
C       NP number of parameters
C       MAXIT maximum allowable number of iterations to be performed
C       NFREQ iteration frequency at which intermediate printing of the current
C          simplex is to be performed to monitor progress toward solution
C       NAMEX name of variable, expressed as five alphanumeric characters
C       XL(I) lower bound on variable (real)
C       XU(I) upper bound on variable (real)
C       X(I) initial value of the variable corresponding to a feasible point
C       NAMEY name of variable, expressed as five alphanumeric characters
C       YL(I) lower bound on variable (real)
C       YU(I) upper bound on variable (real)
C       NAMEP name of parameter, expressed as five alphanumeric characters
C       P(I) value of parameter
C       NAMEF name of objective function, expressed as five alphanumeric characters
C       RDEV allowable relative deviation in objective function value to be
C          used in convergence test ( a value of 0.001 is typical)
C       ADEV allowable absolute deviation in objective function value to be
C          used in convergence test ( a value of 0.001 is typical)
C
C **************************************************************************
C
        DOUBLE PRECISION DSEED
        CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
        *OLD*2
        COMMON/OPT/ F,X(12),Y(30),P(1)
        COMMON/COND1/FLANGE,G,HEAD,V(3),XLL(3,3)
        COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
        *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
        *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
        COMMON/ASTORE/NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
        COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
        DIMENSION TM1(300),TM2(7),TM3(7),TT1(300),T2(7),T3(7)
        ALPHA=1.3
        BETA=0.5
        GAMMA=0.10
        NMAX1=50
```

```
      DSEED=123457.D0
      MAXIT=100
C ..... READ BASIC DATA FOR OPTIMIZATION RUN .....
   99 CALL OPTRD
      CALL OPTPR(1)
C ..... USE OLD SIMPLEX OR NOT? .....
      IF(OLD.EQ.'NO')GOTO 200
      NIT=0
      IND=3
      CALL MODEL(IND)
      KMAX=2*NX
      OPEN(8,FILE='COMP.DAT',STATUS='OLD')
      KCR=KMAX
      GG=0
  808 KPT=KCR
      IF(KCR.GT.7)KPT=7
      INDEX=IGG*7
      DO 802 I=1,NX
      READ(8,3001)(XX(I,K+INDEX),K=1,KPT)
  802 CONTINUE
      IF(NY)804,804,805
  805 DO 806 I=1,NY
      READ(8,3001)(YY(I,K+INDEX),K=1,KPT)
  806 CONTINUE
  804 READ(8,3001)(FF(K+INDEX),K=1,KPT)
      KCR=KCR-7
      IGG=IGG+1
      IF(KCR)807,807,808
  807 CONTINUE
      IND=2
      GOTO 300
  200 CONTINUE
      DO 100 I=1,NX
  100 XC(I)=X(I)
      NIT=0
      IND=1
      CALL IMTST(N1,1,IFLAG,IND)
      CALL OPTPR(2)
      IND=2
      IF(IFLAG)500,501,500
  501 CONTINUE
C ..... ESTABLISH INITIAL SIMPLEX .....
      KMAX=2*NX
      K=1
  104 FF(K)=F
      DO 102 J=1,NX
      XX(I,K)=X(I)
  102 CONTINUE
      IF(NY)120,120,121
  121 CONTINUE
      DO 105 I=1,NY
  105 YY(I,K)=Y(I)
  120 CONTINUE
      DO 103 I=1,NX
  103 XC(I)=(XC(I)*(K-1)+X(I))/K

      IF(K-KMAX)110,300,300
  110 K=K+1
      DO 106 I=1,NX
      CALL GGUBS(DSEED,YFL)
  106 X(I)=XL(I)+YFL*(XU(I)-XL(I))
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)502,503,502
  503 CONTINUE
      GOTO 104
C ..... BEGIN ITERATIVE SEARCH FOR OPTIMUM .....
  300 CONTINUE
C ..... ESTABLISH COUNTER FOR INTERMEDIATE PRINTING .....
      IF(NFREQ)520,520,508
  520 IPRT=MAXIT+1
      GOTO 509
```

```
  508 IPRT=NFREQ
      WRITE(6,1003)
      CALL DPTPR(3)
  509 CDNTINUE
C ..... FIND PDINTS DF SIMPLEX WITH HIGHEST AND LDWEST FUNCTION VAL. ..
  317 NIT=NIT+1
      FMAX=-1.0E10
      FMIN=1.0E10
      JG=0
      JL=0
      DO 323 J=1,KMAX
      IF(FF(J)-FMAX)301,301,303
  303 JG=J
      FMAX=FF(J)
  301 CDNTINUE
      IF(FF(J)-FMIN)322,323,323
  322 FMIN=FF(J)
      JL=J
  323 CONTINUE
C ..... TEST FOR CONVERGENCE .....
      FDEV=FMAX-FMIN

      FTEST=FDEV-FR*ABS(FMIN)-FA
      IF(FTEST)400,400,401
C ..... TEST SATISFIED, PROCEDURE HAS CDNVERGED .....
  400 CALL DPTPR(1)
      WRITE(6,1000)NIT
      DD 404 I=1,NX
      X(I)=XX(I,JL)
  404 CONTINUE
      IF(NY)407,407,406
  406 DD 405 I=1,NY
  405 Y(I)=YY(I,JL)
  407 CONTINUE
      F=FF(JL)
      CALL DPTPR(2)
      GDTO 519
C ..... TEST NOT SATISFIED, PRDCEED FDR ANOTHER ITERATION .....
  401 CONTINUE
C
C     CDMPARE CHANGES IN THE OBJECTIVE FUNCTION BETWEEN ITERATIONS
C     TD AVOID UNNESSARY COMPUTATIDNS WHEN NDT CONVERGE
C
      EPS = 0.001
      AFD1 = ABS(FDEV-FDLD)
      AFD2 = ABS(FDEV-FNEW)
      IF(AFD1.GT.EPS.DR.AFD2.GT.EPS) GOTD 411
      IF(ABS(FDEV/FMIN).LE.0.1) GOTD 511
  411 FDLD = FNEW
      FNEW = FDEV
C
C     CHECK THE NUMBER DF ITERATIDNS AGAINST THE MAXIMUM NUMBER
C
      IF(NIT-MAXIT)402,402,403
C .....  MAXIMUM ALLOWABLE ND. OF ITERATIDN HAS BEEN EXCEEDED .....
  403 CALL DPTPR(1)
      WRITE(6,1001)NIT
      DD 704 I=1,NX

      X(I)=XX(I,JL)
  704 CONTINUE
      IF(NY)707,707,706
  706 DO 705 I=1,NY
  705 Y(I)=YY(I,JL)
  707 CONTINUE
      F=FF(JL)
      CALL DPTPR(3)
      CALL OPTPR(2)
      GOTO 555
  402 CDNTINUE
C
C .....  CDMPUTE CENTRDID OF PDINTS IN SIMPLEX,EXCLUDING ONE
C              WITH HIGHEST FUNCTION VALUE .....
```

```
      DO 304 I=1,NX
      XC(I)=0.0
      DO 305 J=1,KMAX
  305 XC(I)=XC(I)+XX(I,J)
  304 XC(I)=(XC(I)-XX(I,JG))/(KMAX-1)
C ..... COMPUTE NEW TRIAL POINT BY REFLECTING POINT OF HIGHEST
C           FUNCTION VALUE THROUGH CENTROID OF REMAINING POINTS .....
      DO 306 I=1,NX
      X(I)=XC(I)-ALPHA*(XX(I,JG)-XC(I))
C ..... TEST EACH EXPLICIT VARIABLE TO SEE IF IT VIOLATES BOUND.
C           IF SO,SET INSIDE BOUND BY A SMALL AMOUNT .....
      IF(XU(I)-X(I))307,307,308
  307 X(I)=XU(I)-GAMMA*(XU(I)-XC(I))
  308 IF(X(I)-XL(I))309,309,306
  309 X(I)=XL(I)+GAMMA*(XC(I)-XL(I))
  306 CONTINUE
C ..... TEST TO SEE IF IMPLICIT VARIABLES VIOLATE BOUNDS .....
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)504,505,504
  505 CONTINUE
C ..... TEST TO SEE IF TRIAL POINT PRODUCES HIGHEST FUNCTION
C           VALUE IN NEW SIMPLEX .....
      DO 312 J=1,KMAX
      IF(J-JG)316,312,316
  316 IF(FF(J)-F)312,312,313
  312 CONTINUE
C ..... BECAUSE TRIAL POINT PRODUCES HIGHEST FUNCTION VALUE,MOVE
C           TO FRACTIONAL DISTANCE BETA FROM CENTROID OF OTHER POINTS .....
      DO 314 I=1,NX
  314 X(I)=XC(I)+BETA*(X(I)-XC(I))
C ..... INSERT TRIAL POINT INTO NEW SIMPLEX .....
  313 CONTINUE
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)506,507,506
  507 CONTINUE
      DO 315 I=1,NX
  315 XX(I,JG)=X(I)
      IF(NY)520,320,321
  321 CONTINUE
      DO 318 I=1,NY
  318 YY(I,JG)=Y(I)
  320 CONTINUE
      FF(JG)=F
C ..... DO INTERMEDIATE PRINTING IF REQUIRED .....
      IF(NIT-IPRT)317,510,510
  510 CALL OPTPR(4)
      CALL OPTPR(3)
      IPRT=IPRT+NFREQ
      GOTO 317
C ..... PRINT ERROR MESSAGE AFTER CONSTRAINT VIOLATION IN IMTST .....
  500 WRITE(6,1002)
      GOTO 555
  502 CALL FAIL(1)
      GOTO 555
  504 CALL FAIL(2)
      GOTO 555
  506 CALL FAIL(3)
      GOTO 555
  511 WRITE(6,1004) NIT
      WRITE(6,1001) NIT
      CALL OPTPR(3)
      CALL OPTPR(2)
C
C     PRINT TEMPERATURE HISTORY FOR CURRENT TRAY DESIGN
C
  519       WRITE(6,1005)
      T0 = T1
      T1 = TR
```

```
      TW = TC
      TMG = THEAT1
      DO 527 K = 1,3
      CALL HEAT(HJ(K),FII(K),T0,T1,-1.,TMG,251,OEL,TM1,TT1)
      TG = TT1(251)
      CALL COOL(CJ(K),C(K),TL,TG,TW,TM2,T2)
 521        CALL COOLA(CJ(K),C(K),TL,TG,TW,TM3,T3,Z)
      DO 523 K1 = 11,251,10
 523        WRITE(6,1006) TM1(K1), TT1(K1)
      DO 525 K2 = 1,7
      TIME2 = TM1(251) + TM2(K2)
 525        WRITE(6,1006) TIME2, T2(K2)
      DO 527 K3 = 1,7
      TIME3 = TM1(251) + TM2(7) + TM3(K3)
      WRITE(6,1006) TIME3, T3(K3)
  527 CONTINUE
C
C     CALCULATE & PRINT THE OIMENSIONS OF THE TRAY
C
      DO 529 I = 1,3
      XLL(I,3) = X(2)
  529 CONTINUE
      XLL(3,3) = X(2) - 2.*X(1)
      XLL(1,1) = 2. * XLL(1,1)
      XLL(1,2) = 2. * XLL(1,2)
      XLL(2,1) = 2. * XLL(2,1)
      YDU = XLL(3,2)
      ZDO = X(2)
      VDO = XDO * YDO * ZDO
      WRITE(*,*) '    '
      WRITE(*,*) 'ENTREE COMPARTMENT OIMENSION',(XLL(1,I),I=1,3)
      WRITE(*,*) 'STARCH COMPARTMENT DIMENSION',(XLL(2,I),I=1,3)
      WRITE(*,*) 'DESSERT COMPARTMENT OIMENSION',(XDO,YDO,ZDO)
      WRITE(*,*) 'DIMENSION OF INNER DESSERT TRAY',(XLL(3,I),I=1,3)
      WRITE(*,*) 'VOLUME OF (OUTER) OESSERT COMPARTMENT',VDO
  555 STOP
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(/ ' ','PROCEDURE HAS CONVERGED IN',I4,' ITERATIONS.'/
     *' THE SOLUTION IS AS FOLLOWS:')
 1001 FORMAT(' ',/,'PROCEDURE HAS NOT CONVERGED IN',I4,' ITERATIONS.'/
     *' ','THE CURRENT TRIAL SOLUTION ANO SIMPLEX IS AS FOLLOWS:')
 1002 FORMAT(/ ' ','BASE SET OF VARIABLES VIOLATES SOME CONSTRAINT.')
 1003 FORMAT(/ ' ','ITERATION  0')
 1004 FORMAT(/ ' ','NOT MUCH IMPROVEMENT COULO BE ACHIEVEO AFTER ',
     *,I4,'th ITERATION.')
 1005 FORMAT(// ',5X,'AT TIME = min.',5X,'TEMP. = DEG. C.')
 1006 FORMAT(' ',5X,F15.3,5X,F15.3)
 3001 FORMAT(6X,7E15.5)
      END
C
C     Read input data for main optimization program
C -----------------------------------------------------------
      SUBROUTINE OPTRO
C -----------------------------------------------------------
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),

     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
C ..... REAO BASIC DATA .....
      OPEN(5,FILE='OPT2.DAT',STATUS='OLD')
      READ(5,1000)NTITL,OLD
      REAO(5,1001)NX,NY,NP,MAXIT,NFREQ
      DO 100 I=1,NX
```

```
  100 READ(5,1002)NAMEX(I),XL(I),XU(I),X(I)
      IF(NY)112,112,113
  113 DO 101 I=1,NY
  101 READ(5,1002)NAMEY(I),YL(I),YU(I)
  112 CONTINUE
      IF(NP)114,114,115
  115 DO 102 I=1,NP
  102 READ(5,1002)NAMEP(I),P(I)
  114 CONTINUE
      READ(5,1002)NAMEF,FR,FA
      CLOSE(5)
      RETURN
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(A47,A2)
 1001 FORMAT(7I5)
 1002 FORMAT(A5,3F10.4)
      END
C
C     Print intermediate results and optimal design specifications
C ------------------------------------------------------------------
      SUBROUTINE OPTPR(IARG)
C ------------------------------------------------------------------
      DIMENSION NINT(50)
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      DATA NINT/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,
     *22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,
     *43,44,45,46,47,48,49,50/
      GOTO (1,2,3,4,5,6),IARG
    1 CONTINUE
C ..... PRINT TITLE .....
      WRITE(6,2000)NTITL
      RETURN
    2 CONTINUE
C ..... PRINT TRIAL SOLUTION AND LIMITS .....
      WRITE(6,2002)
      WRITE(6,2003)
      DO 200 I=1,NX
  200 WRITE(*,2004)NAMEX(I),XL(I),XU(I),X(I)
      IF(NY)201,201,202
  202 WRITE(6,2005)
      WRITE(6,2003)
      DO 203 I=1,NY
  203 WRITE(6,2004)NAMEY(I),YL(I),YU(I),Y(I)
  201 CONTINUE
      IF(NP)204,204,205
  205 WRITE(6,2011)
      WRITE(6,2012)
      DO 206 I=1,NP
  206 WRITE(6,2004)NAMEP(I),P(I)
  204 CONTINUE
      WRITE(6,2010)
      WRITE(6,2006)
      WRITE(6,2004)NAMEF,F,FR,FA
      RETURN
    3 CONTINUE
C ..... PRINT VALUES OF VARIABLES AT VERTICES OF CURRENT SIMPLEX .....
      KMAX1=KMAX+1
      WRITE(6,2007)KMAX1
```

```
C ..... PRINTING DONE IN GROUPS OF SEVEN .....
      KK=1
      KKK=7
  400 CONTINUE
      KKKK=KKK
      IF(KKK.GE.KMAX1)KKK=KMAX1
      IF(KKK.EQ.KMAX1)KKKK=KKK-1
      WRITE(6,2008)(NINT(I),I=KK,KKK)
      DO 301 I=1,NX
      XX(I,KMAX1)=XC(I)
  301 WRITE(6,2004)NAMEX(I),(XX(I,K),K=KK,KKK)
      IF(NY)303,303,304
  304 DO 305 I=1,NY
  305 WRITE(6,2004)NAMEY(I),(YY(I,K),K=KK,KKKK)
  303 CONTINUE
      WRITE(6,2004)NAMEF,(FF(K),K=KK,KKKK)
      IF(KKK.EQ.KMAX1)GOTO 401
      KK=KK+7
      KKK=KKK+7
      GOTO 400
  401 CONTINUE
      RETURN
    4 CONTINUE
C ..... PRINT RESULTS AT CURRENT ITERATION .....
      WRITE(*,*)' '
      WRITE(6,2009)NIT,JG,FDEV,FMIN
      RETURN
    5 CONTINUE
      RETURN
    6 CONTINUE
      RETURN
C ..... FORMAT STATEMENTS .....
 2000 FORMAT(' ',A47)
 2002 FORMAT(' ','INDEPENDENT VARIABLES')
 2003 FORMAT(' ',1X,'NAME',4X,'LOWER BOUND',4X,'UPPER BOUND',10X,
     *'VALUE'/)
 2004 FORMAT(' ',A5,1P7E15.5)
 2005 FORMAT(' ','DEPENDENT VARIABLES')
 2006 FORMAT(' ',1X,'NAME',10X,'VALUE',8X,'REL DEV',8X,'ABS DEV'/)
 2007 FORMAT(' ','VARIABLES IN SIMPLEX (CENTROID IS VERTEX',I3,')')
 2008 FORMAT(' ','VERTEX',I14,7I15)
 2009 FORMAT(' ','ITERATION',I4,' ENTERING VERTEX',I3,' FDEV =',1PE12.4,
     *' FMIN =',1PE12.4)
 2010 FORMAT(' ','OBJECTIVE FUNCTION')
 2011 FORMAT(' ','PARAMETERS')
 2012 FORMAT(' ',1X,'NAME',10X,'VALUE'/)
      END
C
C     Test for violation of implicit constraints in main program
C ------------------------------------------------------------------
      SUBROUTINE IMTST(N,NMAX,IFLAG,IND)
C ------------------------------------------------------------------
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      IFLAG=0
      N=1
C ..... EVALUATE OBJECTIVE FUNCTION AND DEPENDENT VARIABLES .....
  108 CALL MODEL(IND)
      IF(NY)300,300,301
  300 RETURN
  301 CONTINUE
C ..... TEST TO SEE IF ANY IMPLICIT CONSTRAINT HAS BEEN VIOLATED .....
      DO 103 I=1,NY
      IF(Y(I)-YL(I))101,102,102
  102 IF(YU(I)-Y(I))101,103,103
  103 CONTINUE
```

```
C ..... BECAUSE TRIAL POINT VIOLATES IMPLICIT CONSTRAINTS, MOVE TO
C            FRACTIONAL DISTANCE BETA FROM CENTROID DF OTHER POINTS .....
  101 DD 104 I=1,NX
  104 X(I)=XC(I)+BETA*(X(I)-XC(I))
      IF(N-NMAX)106,107,107
  106 N=N+1
      GOTO 108
C ..... TRIAL POINT DID NOT SATISFY IMPLICIT CONSTRAINT AFTER NMAX
C            MOVES TOWARD CENTROID OF OTHER POINTS .....
  107 IFLAG=1
      RETURN
      END
C
C     Print error messages for main program
C ---------------------------------------------------------------
      SUBROUTINE FAIL(NARG)
C ---------------------------------------------------------------
      WRITE(6,1000)NARG
      CALL OPTPR(2)
      CALL OPTPR(3)
      RETURN
 1000 FORMAT(' ','ERROR ENCOUNTERED IN DPTIMM'/' ','TYPE',I3,
     *' CONSTRAINT VIOLATED')
      END
C
C     Generate random numbers for optimization iterations
C
C ---------------------------------------------------------------
      SUBROUTINE GGUBS (DSEED,R)
C ---------------------------------------------------------------
      REAL R
      DOUBLE PRECISION   DSEED
C       SPECIFICATIONS FOR LOCAL VARIABLES
      INTEGER          I
      DOUBLE PRECISION   D2P31M,D2P31
C      D2P31M=(2**31) - 1
C       D2P31 =(2**31)(OR AN ADJUSTED VALUE)
      DATA          D2P31M/2147483647.D0/
      DATA          D2P31/2147483648.D0/
C       FIRST EXECUTABLE STATEMENT
      DSEED = DMOD(16807.D0*DSEED,D2P31M)
      R = DSEED / D2P31
      RETURN
      END
C
C     Estimate thermal processing lethality and time-temperature history
C     for each of the compartments in the tray
C ---------------------------------------------------------------------
      SUBRDUTINE MODEL(IND)
C ---------------------------------------------------------------------
       CHARACTER*15 MEALS(3)
      DIMENSIDN XL(3),X(3),TTHEAT(3),BI(3),FIMM(3)
      CDMMON/OPT/ OBJ,XI(12),Y(30),PAR(1)
      COMMON/COND1/FLANGE,G,HEAD,V(3),XLL(3,3)
      COMMON/COND/ XKINS,TCDOL,TREF(3),XX(3,3),ZZ(3),FP(3)
     *,XK(3),ALPHA(3),HTA
      COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
C ..... INPUT DATA .....
C     XI(1); INSULATION THICKNESS OF DESSERT TRAY
C     XI(2); HEIGHT OF THE WHOLE TRAY
C     XI(3); LENGTH OF THE ENTREE TRAY
C     G; G BETWEEN TRAYS
C     V(I); VOLUME OF EACH TRAY (INNER VOLUME)
C     XLL(I,J); DIMENSIDN OF ITH TRAY (INNER)
C
C     CDNSTRAINTS FOR TRAY DESIGN
C     LENGTH: <= 11 INCHES
C     DEPTH:  <= 1.1811 INCHES (3 CM)
C     INSULATION THICKNESS: <= 0.6 CM
```

```
C      WIDTH OF SEALING EDGE: 0.6 CM
C      HEIGHT OF HEADSPACE: 0.6 CM
C
       IF(IND.EQ.1.OR.IND.EQ.3) GO TO 10
       GO TO 20
    10 OPEN(UNIT=7,FILE='TRAYDESI1.DAT',STATUS='OLD')
       READ(7,1) G
       READ(7,1) HTA,TCOOL,XKINS
       READ(7,1) TR,TI,TC
       DO 11 I=1,3
       READ(7,2) MEAL$(I)
       READ(7,1) V(I),XX(I,1),XX(I,2),XX(I,3)
       READ(7,3) XK(I),ALPHA(I)
 11    READ(7,1) ZZ(I),TREF(I),FP(I)
       CLOSE (UNIT=7)
       WRITE(6,5) (MEAL$(II),II=1,3)
C ..... CALCULTE THE DIMESION OF THE TRAYS .....
       IF(TREF(3).EQ.100.0) THEN
       FLANGE = 0.006
       HEAD = 0.006
       ELSE
       FLANGE = 0.0
       HEAD = 0.0
       ENDIF
    20 DO 12 I=1,3
       XLL(I,3) = (XI(2) - HEAD)/2.
    12 CONTINUE
       XLL(3,3) = (XI(2) - HEAD - 2.*XI(1))/2.
       XLL(1,1) = XI(3)/2.
       XLL(1,2) = V(1)/(4.*XLL(1,1)*XLL(1,3)) / 2.
       CHECK = 0.3 * XLL(1,1)
       IF(XLL(1,2).GE.CHECK) THEN
       GOTO 14
       ELSE
       XLL(1,1) = SQRT(V(1)/(8.*0.3*XLL(1,3)))
       XLL(1,2) = 0.3 * XLL(1,1)
       ENDIF
    14 AREA2 = V(2) / (2.*XLL(2,3))
       AREA3 = V(3) / (2.*XLL(3,3))
       A = 4.*(XLL(1,1)-0.004-FLANGE)
       B = -4.*FLANGE*(XLL(1,1)-0.004-FLANGE)-AREA2-AREA3
       C1 = FLANGE * AREA2
       XLL(2,2) = (-1.*B + SQRT(B*B - 4.*A*C1)) / (2.*A)
       XLL(2,1) = (V(2)/(4.*XLL(2,2)*XLL(2,3)))/2.
       XLL(3,2) = XLL(2,2) - FLANGE
       XLL(3,1) = XLL(1,1) - XLL(2,1) - 0.004 - FLANGE
       Y(1)=4.*XI(2)*(XLL(3,1)+FLANGE)*(XLL(3,2)+FLANGE)
       IF(XLL(2,2).LE.0.0.OR.XLL(3,3).LE.0.0) Y(1)=-1000.
       IF(Y(1).LT.0.0) RETURN
       Y(2) = XLL(2,2)*2.
       Y(3) = XLL(3,3)*2. + HEAD
C ..... CALCULATE PROCESSING TIME FOR EACH MEAL .....
       T0 = TI
       T1 = TR
       TW = TC
       DO 200 I = 1, 2
       TK=XK(I)
       AL=ALPHA(I)
       Z=ZZ(I)
       TRE=TREF(I)
       DO 100 J=1,3
       XL(J)=XLL(I,J)
       X(J)=XX(I,J)
C      WRITE(6,*) XL(J)
   100 CONTINUE
       HT = HTA
       CALL EIGEN(AL,XL,TK,HT,B1,FH(I),HJ(I))
       CJ(I) = 1.4
       C(I) = FH(I)
       CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,-1.,FP(I),THEAT1,FVALUE)
       IF(THEAT1.GE.300) GO TO 201
       TTHEAT(I) = THEAT1
```

```
      FIMM(I)=FVALUE
  200 CONTINUE
      IF(TTHEAT(1).GT.TTHEAT(2)) THEN
      THEAT1=TTHEAT(1)
      FIMAX=FIMM(1)
      IMAX=1
      ELSE
      THEAT1=TTHEAT(2)
      FIMAX=FIMM(2)
      IMAX=2
      ENDIF
      Y(4) = THEAT1
  201 DO 206 I = 1,3
      IF(I.EQ.IMAX) GOTO 205
      TK=XK(I)
      AL=ALPHA(I)
      Z=ZZ(I)
      TRE=TREF(I)
      DO 204 J=1,3
      XL(J)=XLL(I,J)
      X(J)=XX(I,J)
  204 CONTINUE
      IF(I.NE.3) THEN
      HT = HTA
      ELSE
      HT=1./(1./HTA+XI(1)/XKINS)
      ENDIF
C
C     ESTIMATE THE STERILIZING VALUES FOR ALL THE FOODS BASED ON THE
C     PROCESSING TIME THEAT1 FOR THE FOOD WHICH IS LEAST OVER-PROCESSED.
C
      CALL EIGEN(AL,XL,TK,HT,BI,FH(I),HJ(I))
      CJ(I) = 1.4
      C(I) = FH(I)
      CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,THEAT1,-1.,-1.,FVALUE)
      Y(I+4) = FVALUE
      Y(8) = T(251)
      GO TO 206
  205 Y(I+4) = FIMAX
  206 CONTINUE
      OBJ=ABS(Y(5)-FP(1))+ABS(Y(6)-FP(2))+ABS(Y(7)-FP(3))
      RETURN
C ..... FORMAT STATEMENTS .....
    1 FORMAT(4F10.5)
    2 FORMAT(A10)
    3 FORMAT(F10.4,E10.4)
    5 FORMAT(' MEAL NAMES ARE ',3(A7,2X))
      END
C -----------------------------------------------------------------
C     Calculate f and j values for each meal in the compartment tray
C -----------------------------------------------------------------
      SUBROUTINE EIGEN(AL,XL,TK,HT,BI,FH1,HJ1)
C -----------------------------------------------------------------
      DIMENSION BI(3),XL(3),BETA1(3),FI(3),XJ1(3)
      COMMON/THISTORY/ TRE
      FNF(X,BI1)=X*TAN(X)-BI1
      DO 1240 I=1,3
      BI(I)=HT*XL(I)/TK
      BETA1(I) = 0.0
      STP=3.141592654
      STP1=0.001
      STP2=3.141592654/2.-0.001
      XCRIT=0.00001
      FCRIT=0.0001
      IF(BI(I).EQ.0.0) THEN
      BETA1(I)=0.0
      GO TO 1225
      ELSE
      GO TO 1200
      ENDIF
 1200 X1=STP1
      X2=STP2
```

```
      ICOUNT = 1
1210  F1=FNF(X1,BI(I))
      F2=FNF(X2,BI(I))
1215  FMULT=F1*F2
      IF(FMULT.GT.0.0) GOTO 1225
C ..... BISECTIONAL METHOD FOR ESTIMATION OF ROOTS .....
1000  XERR=ABS(X1-X2)/2.0
      X3=(X1+X2)/2.
      F3=FNF(X3,BI(I))
      IF(I.GT.200) GOTO 1220
      IF(XERR.LT.XCRIT) GO TO 1220
      IF(ABS(F3).LT.FCRIT) GO TO 1220
      IF(F3*F1.LE.0.0) THEN
      X2=X3
      F2=F3
      ELSE
      X1=X3
      F1=F3
      ENDIF
      ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1)BI(I)
      GO TO 1210
 1220 BETA1(I) = X3
      GO TO 1230
 1225 ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1) BI(I)
      X1 = STP + STP1
      X2 = STP + STP2
      F1 = FNF(X1,BI(I))
      F2 = FNF(X2,BI(I))
      GO TO 1215
 1230 FI(I) = LOG(10.0) *XL(I)*XL(I) / (BETA1(I)*BETA1(I)*AL) / 60.
      XJI(I) = 2.0 * SIN(BETA1(I)) / (BETA1(I) +SIN(BETA1(I))*COS(BETA1(I)))
 1240 CONTINUE
      F = 0.0
      HJI = 1.0
      DO 1260 I1 = 1,3
      F = F + 1.0 / FI(I1)
      HJI = HJI * XJI(I1)
 1260 CONTINUE
      FHI = 1.0 / F
 1280 RETURN
    1 FORMAT(' DONT HAVE ROOT OF TRANSCENDENTAL EQUA.',F12.4)
      END
C
C     ESTIMATE PROPER HEAT PROCESSES OF RETORTABLE PLASTIC PACKAGE
C     FOR MULTIPLE FOODS. DEVELOPED MAINLY BASED ON THE PROGRAMS BY
C     DR. K. HAYAKAWA,
C     ADVANCES IN FOOD RESEARCH, VOL. XX. PP. 75-141, 1977.
C     THIS SUBROUTINE SOLVES 2 TYPES OF PROBLEMS. THEY INCLUDE:
C      TYPE B: GIVEN Fp, Solve for tb (thermal processing time)
C      TYPE A: GIVEN tb, Calculate the equivalent Fp
C
C ******************************** NOMENCLATURE ********************************
C     C    Slope index of cooling curve
C     CJ   Intercept coefficient of cooling curve
C     FH   Slope index of heating curve
C     HJ   Intercept coefficient of heating curve
C     FP1  Target sterilizing value
C     FPP  Estimated sterilizing value for given TG or TMG
C     T0   Initial temperature of food (Deg. C.)
C     T1   Holding temperature heating medium (Deg. C.)
C     TANS Length of heating phase to be estimated. A thermal process with TANS
C          minutes of processing time produces a target sterilizing value FP1
C     TG   Food temperature at end of heating phase of thermal process.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TG = - 1.0.
C     TMG  Length of heating phase.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TMG = -1.0
C     TW   Cooling medium temperature (Deg. C.)
      ***********************************************************************
```

```
C -----------------------------------------------------------------
      SUBROUTINE PROCESS(T0,T1,TW,HJ,FH,CJ,C,Z,TG,TMG,FP1,TANS,FPP)
C -----------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
      ABC(1)=-1.0
      ABC(2)=-0.8302239
      ABC(3)=-0.4688488
      ABC(4)=0.0
      ABC(5)=0.4688488
      ABC(6)=0.8302239
      ABC(7)=1.0
      H(1)=0.0476190
      H(2)=0.2768260
      H(3)=0.4317454
      H(4)=0.4876190
      H(5)=0.4317454
      H(6)=0.2768260
      H(7)=0.0476190
      DO 141 J=1,300
      T(J)=0.
  141 TM(J)=0.
      FPP=0.
      YFP = 0.
      YFP1 = 0.
      YFP2 = 0.
      TANS=0.
      IF(FP1.LE.0.) GO TO 146
C
C     This is a Type B Problem.
C     It solves for the processing time TANS to achieve target Fp.
C
      TMG1 = FP1
      FPP = 0.
      TMG2 = 40. * FP1
  142 TMG = TMG1
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH1)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP1 = FPH1 + FPC
      YFP1 = FP1 - FPP1
  143 TMG = TMG2
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH2)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP2 = FPH2 + FPC
      YFP2 = FP1 - FPP2
      TMG = (TMG1+TMG2) / 2.0
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP = FPH + FPC
      YFP = FP1 - FPP
      IF((YFP1*YFP).GT.0..AND.(YFP2*YFP).GT.0.) GOTO 148
      IF(ABS(FPP-FP1).LE.0.1) GO TO 144
      YCHECK = YFP1 * YFP
      IF(YCHECK.LE.0.0) THEN
      TMG2 = TMG
      GO TO 143
      ELSE
      TMG1 = TMG
      GO TO 142
      ENDIF
  144 TANS = TMG
      GO TO 150
C
C     This is a type A problem.
C     Given heating time, solve for actual Fp.
```

```
 146 TG = T1 - HJ *(T1-T0) * 10.**(-TMG /FH)
     CALL HEAT(HJ,FH,T0,T1,TG,-1.0,251,DEL,TM,T)
     CALL SIMP(T,OEL,251,Z,FPH)
     CALL FCOL(FPC,CJ,C,T(251),TW,Z)
     FPP = FPH + FPC
     GO TO 150
 148 WRITE(6,149)
 149 FORMAT('  ','PROCESSING TIME IS LARGER THAN 40 Fp.'/,
    *'  ','Please modify the program!')
 150 RETURN
     END
C
C     Calcualte food temperatures on a heating curve
C     The equations were updated (from the 1977 Reference)
C     with reference to Lekwauwa, A. N. and Hayakawa, K., 1986.
C     J. Food Sci. 51(4): 1042-1049, 1056.
C
C ************************** NOMENCLATURE **************************
C     DEL  Time increment for heating phase
C     NTRM Number of food temperatures to be estimated. 2 < NTRM <= 300
C     T    Food temperature estimated (Deg. C.)
C     TM   Heating times at which food temperatures reach to T's
C *******************************************************************
C -----------------------------------------------------------
      SUBROUTINE HEAT(HJ,FH,T0,T1,TG,TMG,NTRM,DEL,TM,T)
C -----------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION T(300),TM(300)
      AN(A,AF,AJ) = (A/AF - ALOG10(AJ)) / (A/AF)
      BA(AJ,A,AF,BN) = A* (A/AF - ALOG10(AJ))**(BN)
      TA(TMA,BAA,AAN)=T1-(T1-T0)*EXP(-2.30259*EXP(ALOG(
     *TMA/BAA)*(1./AAN)))
      TIA(BAA,TP,AAN)=BAA*((ALOG10((T1-T0)/(T1-TP)))**AAN)
      BB(TLB)=(1./TLB)*(ATAN((ALOG10(T1-T0))/(ALOG10(HJ*(T1-T0))-TLB/FH))
     *- 0.785398)
      TB(BBB,TMB)=T1-(T1-T0)**(1./TAN(BBB*TMB+0.785398))

      TIB(BBB,TP)=(1./BBB)*(ATAN((ALOG10(T1-T0))/(ALOG10(T1-TP)))-0.785398)
      BC(TLC)=(1./TLC)*ACOS((ALOG10(HJ*(T1-T0))-TLC/FH)/(ALOG10(T1-T0)))
      TC(BCC,TMC)=T1-(T1-T0)**(COS(BCC*TMC))
      TIC(BCC,TP)=(1./BCC)*ACOS((ALOG10(T1-TP))/(ALOG10(T1-T0)))
      TD(TMD)=T1-HJ*(T1-T0)*EXP(-2.30259*(TMD/FH))
      TID(TP)=FH*ALOG10(HJ*(T1-T0)/(T1-TP))
      DO 90 I=1,300
      T(I)=0.0
   90 TM(I)=0.0
      NXX=NTRM-1
      IF(HJ.LT.0.001)GO TO 1
      IF(HJ.LT.0.40)GO TO 2
      IF(HJ.LE.0.999999)GO TO 3
      IF(HJ.LE.1.00001)GO TO 7
      IF(HJ.GT.6500.0)GO TO 4
      GO TO 6
    1 WRITE(*,5)
    5 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH < 0.001')
    2 TL = FH * (0.3913 - 0.3737 * ALOG10(HJ))
      RN = AN(TL,FH,HJ)
      B = BA(HJ,TL,FH,RN)
      IF(TG.LT.0.0)GO TO 8
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 9
      TMH=TID(TG)
      TH=TG
      GO TO 10
    9 TMH=TIA(B,TG,RN)
      TH=TG
      GO TO 10
    8 IF(TMG.LT.TL)GO TO 11
      TH=TD(TMG)
      TMH=TMG
      GO TO 10
   11 TH=TA(TMG,B,RN)
```

```
      TMH=TMG
   10 T(1)=T0
      TM(1)=0.
      DEL=TMH/NXX
      T(NTRM)=TH
      TM(NTRM)=TMH
      DO 100 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 102
      T(I)=TA(TMI,B,RN)
      GO TO 100
  102 T(I)=TD(TMI)
  100 CONTINUE
      GO TO 60
    3 TL = 0.9*FH*(1.-HJ)
      B = BB(TL)
      IF(TG.LT.0.0)GO TO 19
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 20
      TMH=TID(TG)
      TH=TG
      GO TO 21
   20 TMH=TIB(B,TG)
      TH=TG
      GO TO 21
   19 IF(TMG.LT.TL)GO TO 22
      TH=TD(TMG)
      TMH=TMG
      GO TO 21
   22 TH=TB(B,TMG)
      TMH=TMG
   21 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 30 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 32
      T(I)=TB(B,TMI)
      GO TO 30
   32 T(I)=TD(TMI)
   30 CONTINUE
      GO TO 60
    7 IF(TG.LT.0.0)GO TO 34
      TMH=TID(TG)
      TH=TG
      GO TO 35
   34 TH=TD(TMG)
      TMH=TMG
   35 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 40 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      T(I)=TD(TMI)
   40 CONTINUE
      GO TO 60
    4 WRITE(*,43)
   43 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH > 6500.0')
    6 IF(HJ.LE.5.8) TL = 0.7*FH*(HJ-1.)
      IF(HJ.GT.5.8) TL = 1.54 *FH *ALOG10(HJ/1.8)
      B = BC(TL)
      IF(TG.LT.0.0)GO TO 44
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 45
```

```
      TMH=TID(TG)
      TH=TG
      GO TO 46
   45 TMH=TIC(B,TG)
      TH=TG
      GO TO 46
   44 IF(TMG.LT.TL)GO TO 47
      TH=TD(TMG)
      TMH=TMG
      GO TO 46
   47 TH=TC(B,TMG)
      TMH=TMG
   46 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 55 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 57
      T(I)=TC(B,TMI)
      GO TO 55
   57 T(I)=TD(TMI)
   55 CONTINUE
   60 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM TWO FOOD TEMPERATURES
C     DEL MINUTE APART from each other DURING THE HEATING PHASE
C
C***************************** NOMENCLATURE ******************************
C     DELF Estimated sterilizing value (min.)
C     TH Food temperature (TH > TL)
C     TL Food temperature (TL < TH)
C     Z  Slope index of thermal death time curve (C. Deg.)
C*************************************************************************
C ---------------------------------------------------------------
      SUBROUTINE FDIF(DELF,T1,TH,TL,DEL,Z)
C ---------------------------------------------------------------
      TM=FTG(T1,TH,TL,0.5*DEL,0.,DEL)
      DELF=DEL/6.0*(RT(TL,Z)+4.*RT(TM,Z)+RT(TH,Z))
      RETURN
      END
C ---------------------------------------------------------------
      FUNCTION RT(T,Z)
C ---------------------------------------------------------------
      COMMON/THISTORY/ TRE
      IF(ABS(T-TRE).LT.1.E-5)GO TO 1
      TRAT=(T-TRE)/Z
      IF(TRAT.LT.-6.0)GO TO 3
      RT=10.**TRAT
      GO TO 2
    3 RT=1.0E-6
      GO TO 2
    1 RT=1.0
    2 RETURN
      END
C ---------------------------------------------------------------
      FUNCTION FX(FA,FB,TA,TB,TX)
C ---------------------------------------------------------------
      FX=FA+(TX-TA)*(FB-FA)/(TB-TA)
      RETURN
      END
C ---------------------------------------------------------------
      FUNCTION FTG(T1,TH,TL,TMG,TML,DEL)
C ---------------------------------------------------------------
      IF(ABS(TMG-TML).LE.1.E-5)GO TO 1
      IF(ABS(T1-TH).LE.1.E-5)GO TO 2
      R=(T1-TH)/(T1-TL)
      IF(R.GE.0.9999)GO TO 2
      FTG=T1-(T1-TL)*R**((TMG-TML)/DEL)
```

```
      GO TO 3
    1 FTG=TL
      GO TO 3
    2 FTG=(TH+TL)/2.
    3 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM A COOLING CURVE
C
C ****************************** NOMENCLATURE ****************************
C     FPC Estimated sterilizing value (min.) during cooling phase
C ************************************************************************
C -------------------------------------------------------------
      SUBROUTINE FCOL(FPC,CJ,C,TG,TW,Z)
C -------------------------------------------------------------
      COMMON/THISTORY/ TRE
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      DIMENSION TMC(7),TC(7)
      DO 1 I=1,7
      TMC(I)=0.
    1 TC(I)=0.
      IF(ABS(CJ-1.0).LT.1.0E-4)GO TO 2
      CALL COOL(CJ,C,TL,TG,TW,TMC,TC)
      CALL RATE(FPA,TC,Z,0.,TL)
      GO TO 3
    2 FPA=0.
      TL=0.
    3 CALL COOLA(CJ,C,TL,TG,TW,TMC,TC,Z)
      CALL RATE(FPB,TC,Z,TL,TMC(7))
      FPC=FPA+FPB
      RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM DATA ON FOOD
C     TEMPERATURE COLLECTED AT UNIFORM TIME INTERVALS
C
C ****************************** NOMENCLATURE ****************************
C     DELX uniform time interval (min.)
C     NO   Number of temperature data collected
C     Y    Vector of temperature data (Deg. C.)
C ************************************************************************
C -------------------------------------------------------------
      SUBROUTINE SIMP(Y,DELX,N0,Z,FP)
C -------------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION Y(300)
      NN=N0/2
      NM=NN*2
      F(NM.EQ.N0)GO TO 10
      NM=N0
      GO TO 11
   10 NM=N0-1
   11 IF(N0-3)1,2,3
    1 IF(N0.EQ.2)GO TO 12
      IF(N0.EQ.1)GO TO 13
      WRITE(*,14)
   14 FORMAT(' ','NO FP IS ESTIMATED SINCE N0 < 1 AT SUBROUTINE SIMP')
   13 FP=0.
      GO TO 6
    2 FP=DELX/3.*(RT(Y(1),Z)+4.*RT(Y(2),Z)+RT(Y(3),Z))
      GO TO 6
    3 FP=RT(Y(1),Z)+RT(Y(NM),Z)
      M=NM-1
      FPA=0.
      DO 4 I=2,M,2
    4 FPA=FPA+RT(Y(I),Z)
      IF(N0.EQ.4)GO TO 15
      FPB=0.
      M=NM-2
      DO 5 I=3,M,2
    5 FPB=FPB+RT(Y(I),Z)
```

```
      GO TO 16
   15 FP=DELX/3.*(FP+4.*FPA)
      GO TO 20
   16 FP=DELX/3.*(FP+4.*FPA+2.*FPB)
      IF(NM.EQ.N0)GO TO 6
   20 FP=FP+DELX/2.*(RT(Y(N0-1),Z)+RT(Y(N0),Z))
      GO TO 6
   12 FP=DELX/2.*(RT(Y(1),Z)+RT(Y(2),Z))
    6 RETURN
      END
C
C     CALCULATE 7 TEMPERATURES ON A CURVILINEAR PORTION OF
C     A COOLING CURVE. THESE TEMPERATURES ARE THEN USED TO
C     CALCULATE A STERILIZING VALUE BY USING THE 7 POINT
C     LOBBATO QUADRATURE FORMULA.
C
C******************************** NOMENCLATURE ************************
C     FC   Slope index of cooling curve
C**********************************************************************
C ---------------------------------------------------------------
      SUBROUTINE COOL(CJ,FC,TL,TG,TW,TM,T)
C ---------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      DIMENSION TM(7),T(7)
      TXA(Y,BY,YN)=TW+(TG-TW)*EXP(-2.302585*EXP(ALOG(Y/BY)*(1./YN)))
      TXB(Y,BY)=TW+(TG-TW)**(1./TAN(BY*Y+0.785398))
      TXC(Y,BY)=TW+(TG-TW)**(COS(BY*Y))
      TMX(X,TK)=TK/2.+TK*X/2.
      DO 50 I=1,7
      TM(I)=0.
   50 T(I)=0.
      IF(CJ.GE.0.001)GO TO 11
   10 WRITE(*,12)
   12 FORMAT(1X,'TM & T VLAUES ESTIMATED BY SUBROUTINE COOL ARE QUESTI
     *ONABLE SINCE CJ < 0.001')
      GO TO 13
   11 IF(CJ.LE.0.4)GO TO 13
      IF(CJ.LE.0.999999)GO TO 14
      IF(CJ.LE.1.00001)GO TO 15
      IF(CJ.LE.6500.0)GO TO 16
      WRITE(*,17)
   17 FORMAT(1X,'TM & T VALUES ESTIMATED BY COOL ARE QUESTION
     *ABLE SINCE CJ > 6500.0')
      GO TO 16
   13 TL = FC * (0.3913 - 0.3737 * ALOG10(CJ))
      EN = (TL/CJ - ALOG10(CJ)) / (TL/CJ)
      B = TL * (TL/CJ - ALOG10(CJ))**(EN)
      T(1)=TG
      TM(1)=0.
      DO 18 I=2,7
      IF(I.EQ.4)GO TO 19
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   20 TXT=TXA(TM(I),B,EN)
      T(I)=TXT
      GO TO 18
   19 TM(I)=TL/2.
      GO TO 20
   18 CONTINUE
      GO TO 8
   15 WRITE(*,21)
   21 FORMAT(1X,'CALLING EXIT FROM COOL SINCE CJ=1.0')
      GO TO 8
   14 TL=0.9*FC*(1.-CJ)
      B=(1./TL)*(ATAN(ALOG10(TG-TW)/(ALOG10(CJ*(TG-TW))-TL/FC))-0.7853982)
      TM(1)=0.
      T(1)=TG
      DO 22 I=2,7
      IF(I.EQ.4)GO TO 23
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
```

```
 24 TXT=TXB(TM(I),B)
    T(I)=TXT
    GO TO 22
 23 TM(I)=TL/2.
    GO TO 24
 22 CONTINUE
    GO TO 8
 16 IF(CJ.LE.5.8) TL=0.7*FC*(CJ-1.)
    IF(CJ.GT.5.8) TL = 1.54 *FC *ALOG10(CJ/1.8)
    B=(1.0/TL)*ACOS((ALOG10(CJ*(TG-TW))-TL/FC)/ALOG10(TG-TW))
    TM(1)=0.
    T(1)=TG
    DO 25 I=2,7
    IF(I.EQ.4)GO TO 26
    TMZ=TMX(ABC(I),TL)
    TM(I)=TMZ
 27 TXT=TXC(TM(I),B)
    T(I)=TXT
    GO TO 25
 26 TM(I)=TL/2.
    GO TO 27
 25 CONTINUE
  8 RETURN
    END
C
C     CALCULATE 7 TEMPERATURES ON A LINEAR PORTION
C     OF A COOLING CURVE
C ------------------------------------------------------------------
      SUBROUTINE COOLA(CJ,FC,TL,TG,TW,TM,T,Z)
C ------------------------------------------------------------------
      DIMENSION TM(7),T(7)
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      TX(Y)=TW+CJ*(TG-TW)*EXP(-2.302585*Y/FC)
      TMX(X,TBX,TIN)=(TBX+TIN)/2.+(TBX-TIN)*X/2.
      TMY(X,TBX)=TBX/2.+TBX*X/2.
      TIM(X)=FC*ALOG10(CJ*(TG-TW)/(X-TW))
      DO 50 I=1,7
      TM(I)=0.0
   50 T(I)=0.0
      IF(CJ.LE.0.999999)GO TO 8
      IF(CJ.LE.1.00001)GO TO 9
      GO TO 8
    9 TBL=TG
C ..... WHEN CJ=1.0,THE COMPUTATIONAL FLOW IS BLANCHED TO 9. IN
C       THIS CASE TBL=TG SINCE THERE IS NO CURVELINEAR PORTION.....
      GO TO 10
    8 TBL=TX(TL)
   10 IF(TRE.NE.(5.*Z))GO TO 20
      TLOW=1.E-6
      GO TO 21
   20 TLOW=TRE - 5.*Z
   21 IF(TLOW.GE.TG)GO TO 1
      IF(TLOW.GE.TBL)GO TO 1
      IF(TLOW.GT.TW)GO TO 2
      IF(TLOW.LE.TW)GO TO 3
    1 TEND=TIM((TBL+TW)/2.)
    7 CONTINUE
      T(1)=TBL
      TM(1)=TL
      DO 4 I=2,7
      IF(I.EQ.4)GO TO 5
      IF(CJ.LE.0.999999)GO TO 11
      IF(CJ.LE.1.00001)GO TO 12
   11 TMT=TMX(ABC(I),TEND,TL)
    6 TM(I)=TMT
      GO TO 13
   12 TMT=TMY(ABC(I),TEND)
      GO TO 6
   13 T(I)=TX(TMT)
      GO TO 4
    5 IF(CJ.LE.0.999999)GO TO 14
```

```
      IF(CJ.LE.1.00001)GO TO 15
   14 TMT=(TEND+TL)/2.
      GO TO 6
   15 TMT=TEND/2.
      GO TO 6
    4 CONTINUE
      GO TO 16
    2 TEND=TIM(TLOW)
      GO TO 7
    3 TEND=TIM(TW+0.01*(TBL-TW))
      GO TO 7
   16 RETURN
      END
C
C     CALCULATE STERILIZING VALUES BY
C     APPLYING LOBBATO 7 POINT QUADRATURE FORMULA
C
C **************************** NOMENCLATURE ****************************
C     R    Sterilizing value calculated (min.)
C     T    Seven temperatures (Deg. C.) used to calculate R value.
C     TBGIN Lower time limit of integration (min.)
C     TEND  Upper time limit of integration (min.)
C ***********************************************************************
C ------------------------------------------------------------
      SUBROUTINE RATE(R,T,Z,TBGIN,TEND)
C ------------------------------------------------------------
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      DIMENSION T(7)
      IF(T(1).NE.TRE)GO TO 2
      RA=H(1)
      GO TO 4
    2 RA=H(1)*10.**((T(1)-TRE)/Z)
    4 CONTINUE
      DO 1 I=2,7
      IF(T(I).NE.TRE)GO TO 5
      RA=RA+H(I)
      GO TO 1
    5 RA=RA+H(I)*10.**((T(I)-TRE)/Z)
    1 CONTINUE
      IF(TBGIN.GE.1.0E-3)GO TO 6
      R=TEND/2.*RA
      GO TO 7
    6 R=(TEND-TBGIN)/2.*RA
    7 RETURN
      END
```

APPENDIX H

ONE-TRAY DESIGN COMPUTER PROGRAM

8.2 EXAMPLE OF OUTPUT FROM ONE-TRAY CONCEPT PROGRAM-OP3.F

TRAY DESIGN OF MULTICOMPARTMENT M.R.E.
MEAL NAMES ARE chichen potato apple d
INDEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
INSUL	0.00000E+00	4.00000E-03	4.00000E-03
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02
LEN	1.85800E-01	1.85800E-01	1.85800E-01
VDI	2.23000E-04	2.25000E-04	2.24000E-04
VS	1.70000E-04	1.71000E-04	1.70000E-04
VE	2.28000E-04	2.30000E-04	2.29000E-04

DEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
VDO	0.00000E+00	1.00000E+00	4.07382E-04
WSC	6.00000E-02	2.00000E-01	1.20300E-01
DDSRT	1.50000E-02	3.60000E-02	3.40872E-02
HTIME	1.00000E+01	2.00000E+02	2.81708E+01
FE	6.00000E+00	1.50000E+01	6.36309E+00
FS	6.00000E+00	1.50000E+01	6.05329E+00
FD	1.00000E+00	3.10000E+03	2.95315E+00
TFIN	9.10000E+01	1.21100E+02	9.67900E+01

OBJECTIVE FUNCTION

NAME	VALUE	REL DEV	ABS DEV
DEVIA	4.56656E-01	1.00000E-02	1.00000E-01

ITERATION 0
VARIABLES IN SIMPLEX (CENTROID IS VERTEX 13)

VERTEX	1	2	3	4	5
INSUL	4.00000E-03	3.86488E-03	3.94874E-03	1.95494E-03	1.38398E-03
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01
VDI	2.24000E-04	2.24139E-04	2.23762E-04	2.23394E-04	2.24797E-04
VS	1.70000E-04	1.70845E-04	1.70016E-04	1.70090E-04	1.70289E-04
VE	2.29000E-04	2.28089E-04	2.29174E-04	2.28790E-04	2.29797E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01
DDSRT	3.40872E-02	3.38294E-02	3.39633E-02	2.99427E-02	2.89267E-02
HTIME	2.81708E+01	2.84031E+01	2.81708E+01	2.81708E+01	2.84031E+01
FE	6.36309E+00	6.64337E+00	6.34593E+00	6.38403E+00	6.47171E+00
FS	6.05329E+00	6.12741E+00	6.05121E+00	6.04184E+00	6.19958E+00
FD	2.95315E+00	3.85916E+00	3.19804E+00	6.47425E+01	1.59476E+02
TFIN	9.67900E+01	9.79931E+01	9.71607E+01	1.10708E+02	1.14400E+02
DEVIA	4.56656E-01	1.32994E+00	3.92762E-01	6.19847E+01	1.56847E+02

VERTEX	8	9	10	11	12
INSUL	2.63870E-03	1.94039E-03	3.81747E-03	3.10620E-03	3.02728E-03
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01
VDI	2.24233E-04	2.24162E-04	2.23661E-04	2.24904E-04	2.24700E-04
VS	1.70680E-04	1.70727E-04	1.70918E-04	1.70105E-04	1.70875E-04
VE	2.29421E-04	2.28576E-04	2.28348E-04	2.28180E-04	2.29759E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01
DDSRT	3.13854E-02	2.99825E-02	3.36917E-02	3.23807E-02	3.22045E-02
HTIME	2.84031E+01	2.84031E+01	2.84031E+01	2.81708E+01	2.84031E+01
FE	6.50926E+00	6.59413E+00	6.61712E+00	6.44466E+00	6.47542E+00
FS	6.14865E+00	6.14241E+00	6.11777E+00	6.03991E+00	6.12348E+00
FD	2.31563E+01	6.87606E+01	4.20005E+00	1.02365E+01	1.26025E+01
TFIN	1.06174E+02	1.10929E+02	9.83847E+01	1.02532E+02	1.03436E+02
DEVIA	2.05142E+01	6.61972E+01	1.63494E+00	7.54126E+00	9.90140E+00

ITERATION 10 ENTERING VERTEX 2 FDEV = 9.3718E-01 FMIN = 3.9276E-01
VARIABLES IN SIMPLEX (CENTROID IS VERTEX 13)

VERTEX	1	2	3	4	5
INSUL	4.00000E-03	3.99576E-03	3.94874E-03	3.96432E-03	3.91001E-0
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-0
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-0
VDI	2.24000E-04	2.23052E-04	2.23762E-04	2.24520E-04	2.23201E-04
VS	1.70000E-04	1.70006E-04	1.70016E-04	1.70956E-04	1.70808E-04
VE	2.29000E-04	2.28875E-04	2.29174E-04	2.28423E-04	2.28082E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-0
DDSRT	3.40872E-02	3.39937E-02	3.39633E-02	3.40624E-02	3.38356E-0
HTIME	2.81708E+01	2.81708E+01	2.81708E+01	2.84031E+01	2.84031E+0
FE	6.36309E+00	6.37547E+00	6.34593E+00	6.60949E+00	6.64387E+0
FS	6.05329E+00	6.05230E+00	6.05121E+00	6.11293E+00	6.13216E+0
FD	2.95315E+00	3.09643E+00	3.19804E+00	3.30650E+00	3.76981E+0
TFIN	9.67900E+01	9.70076E+01	9.71607E+01	9.72752E+01	9.78810E+0
DEVIA	4.56656E-01	3.26742E-01	3.92762E-01	7.28917E-01	1.24583E+0

VERTEX	8	9	10	11	12
INSUL	3.97637E-03	3.94621E-03	3.99458E-03	3.99299E-03	3.98500E-0
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-0
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-0
VDI	2.23489E-04	2.23499E-04	2.23473E-04	2.23063E-04	2.23080E-04
VS	1.70459E-04	1.70296E-04	1.70072E-04	1.70955E-04	1.70118E-04
VE	2.28054E-04	2.28717E-04	2.28461E-04	2.28621E-04	2.28038E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-0
DDSRT	3.39941E-02	3.39347E-02	3.40291E-02	3.39892E-02	3.39747E-0
HTIME	2.84031E+01	2.84031E+01	2.81708E+01	2.84031E+01	2.81708E+0
FE	6.64680E+00	6.57992E+00	6.41670E+00	6.58958E+00	6.45887E+0
FS	6.17750E+00	6.19848E+00	6.04388E+00	6.11313E+00	6.03803E+0
FD	3.40737E+00	3.54175E+00	3.04186E+00	3.39107E+00	3.13571E+0
TFIN	9.74114E+01	9.75917E+01	9.69262E+01	9.73876E+01	9.70665E+0
DEVIA	9.31661E-01	1.02015E+00	4.30966E-01	7.93771E-01	4.56542E-0

NOT MUCH IMPROVEMENT COULD BE ACHIEVED AFTER 19th ITERATION.

PROCEDURE HAS NOT CONVERGED IN 19 ITERATIONS.
THE CURRENT TRIAL SOLUTION AND SIMPLEX IS AS FOLLOWS:
VARIABLES IN SIMPLEX (CENTROID IS VERTEX 13)

VERTEX	1	2	3	4	5
INSUL	4.00000E-03	3.99576E-03	3.94874E-03	3.99907E-03	3.99753E-0
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-0
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-0
VDI	2.24000E-04	2.23052E-04	2.23762E-04	2.23073E-04	2.23872E-04
VS	1.70000E-04	1.70006E-04	1.70016E-04	1.70005E-04	1.70032E-04
VE	2.29000E-04	2.28875E-04	2.29174E-04	2.29829E-04	2.29243E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-0
DDSRT	3.40872E-02	3.39937E-02	3.39633E-02	3.40022E-02	3.40708E-0
HTIME	2.81708E+01	2.81708E+01	2.81708E+01	2.81708E+01	2.81708E+0
FE	6.36309E+00	6.37547E+00	6.34593E+00	6.28119E+00	6.33896E+0
FS	6.05329E+00	6.05230E+00	6.05121E+00	6.05251E+00	6.04904E+0
FD	2.95315E+00	3.09643E+00	3.19804E+00	3.07872E+00	2.98037E+0
TFIN	9.67900E+01	9.70076E+01	9.71607E+01	9.69809E+01	9.68323E+0
DEVIA	4.56656E-01	3.26742E-01	3.92762E-01	2.49965E-01	4.09556E-0

VERTEX	8	9	10	11	12
INSUL	3.99884E-03	3.98047E-03	3.99458E-03	3.98368E-03	3.98500E-0
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-02	3.15600E-0
LEN	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-01	1.85800E-0
VDI	2.23870E-04	2.23507E-04	2.23473E-04	2.24593E-04	2.23080E-0
VS	1.70022E-04	1.70003E-04	1.70072E-04	1.70013E-04	1.70118E-0

VE	2.29853E-04	2.29511E-04	2.28461E-04	2.29374E-04	2.28038E-04
VDO	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04	4.07382E-04
WSC	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01	1.20300E-01
DDSRT	3.40732E-02	3.40039E-02	3.40291E-02	3.41077E-02	3.39747E-02
HTIME	2.81708E+01	2.81708E+01	2.81708E+01	2.81708E+01	2.81708E+01
FE	6.27876E+00	6.31259E+00	6.41670E+00	6.32602E+00	6.45887E+00
FS	6.05026E+00	6.05277E+00	6.04388E+00	6.05164E+00	6.03803E+00
FD	2.97465E+00	3.09835E+00	3.04186E+00	2.94455E+00	3.13571E+00
TFIN	9.68234E+01	9.70121E+01	9.69262E+01	9.67785E+01	9.70665E+01
DEVIA	3.53853E-01	2.61465E-01	4.30966E-01	4.29825E-01	4.56542E-01

INDEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
INSUL	0.00000E+00	4.00000E-03	3.99907E-03
HEIGT	3.15600E-02	3.15600E-02	3.15600E-02
LEN	1.85800E-01	1.85800E-01	1.85800E-01
VDI	2.23000E-04	2.25000E-04	2.23073E-04
VS	1.70000E-04	1.71000E-04	1.70005E-04
VE	2.28000E-04	2.30000E-04	2.29829E-04

DEPENDENT VARIABLES

NAME	LOWER BOUND	UPPER BOUND	VALUE
VDO	0.00000E+00	1.00000E+00	4.07382E-04
WSC	6.00000E-02	2.00000E-01	1.20300E-01
DDSRT	1.50000E-02	3.60000E-02	3.40022E-02
HTIME	1.00000E+01	2.00000E+02	2.81708E+01
FE	6.00000E+00	1.50000E+01	6.28119E+00
FS	6.00000E+00	1.50000E+01	6.05251E+00
FD	1.00000E+00	3.10000E+03	3.07872E+00
TFIN	9.10000E+01	1.21100E+02	9.69809E+01

OBJECTIVE FUNCTION

NAME	VALUE	REL DEV	ABS DEV
DEVIA	2.49965E-01	1.00000E-02	1.00000E-01

AT TIME = min.	TEMP. = DEG. C.
1.127	26.450
2.254	30.660
3.380	37.236
4.507	45.595
5.634	55.050
6.761	64.911
7.888	74.565
9.015	83.426
10.141	90.353
11.268	96.007
12.395	100.621
13.522	104.386
14.649	107.459
15.776	109.968
16.902	112.015
18.029	113.685
19.156	115.048
20.283	116.161
21.410	117.069
22.537	117.810
23.663	118.415
24.790	118.909
25.917	119.312
27.044	119.641
28.171	119.909
28.171	119.909

28.474	119.685
29.120	117.738
29.959	112.438
30.797	104.532
31.443	97.142
31.746	93.406
35.322	93.406
35.648	89.212
36.343	81.064
37.244	71.906
38.145	64.121
38.840	58.927
39.166	56.703
1.127	26.439
2.254	30.620
3.380	37.153
4.507	45.463
5.634	54.871
6.761	64.695
7.888	74.325
9.015	82.988
10.141	89.852
11.268	95.480
12.395	100.094
13.522	103.877
14.649	106.979
15.776	109.522
16.902	111.607
18.029	113.317
19.156	114.719
20.283	115.868
21.410	116.810
22.537	117.583
23.663	118.216
24.790	118.736
25.917	119.161
27.044	119.511
28.171	119.797
28.171	119.797
28.481	119.573
29.142	117.628
30.000	112.334
30.858	104.437
31.519	97.055
31.829	93.324
35.488	93.324
35.822	89.134
36.533	80.996
37.455	71.848
38.377	64.072
39.087	58.884
39.421	56.662
1.127	25.287
2.254	26.142
3.380	27.549
4.507	29.482
5.634	31.904
6.761	34.771
7.888	38.032
9.015	41.632
10.141	45.510
11.268	49.605
12.395	53.855

13.522	58.201
14.649	62.580
15.776	66.753
16.902	70.628
18.029	74.227
19.156	77.569
20.283	80.673
21.410	83.555
22.537	86.232
23.663	88.718
24.790	91.027
25.917	93.172
27.044	95.163
28.171	97.012
28.171	97.012
29.005	96.839
30.779	95.338
33.081	91.251
35.384	85.156
37.158	79.461
37.992	76.583
47.813	76.583
48.710	73.350
50.618	67.070
53.093	60.010
55.568	54.010
57.476	50.006
58.372	48.292

```
ENTREE COMPARTMENT DIMENSION  0.1858000      5.5750001E-02  2.2157073E-02
STARCH COMPARTMENT DIMENSION  7.0500001E-02  0.1203000      2.0044826E-02
DESSERT COMPARTMENT DIMENSION  0.1073000      0.1203000      2.0042988E-02
DIMENSION OF INNER DESSERT TRAY  9.9299997E-02  0.1123000      2.0042988E-02
VOLUME OF (OUTER) DESSERT COMPARTMENT  2.5871870E-04

STOP
```

8 EXAMPLES OF RUNNING ONE-TRAY CONCEPT PROGRAM-OP3.F

8.1 EXAMPLE OF INPUT FILE

8.1.1 EXAMPLE OF OPT3.DAT

```
TRAY DESIGN OF MULTICOMPARTMENT M.R.E.          NO
    6     8     0  200   10
INSUL  0.000       0.004    0.004
HEIGT  0.03156     0.03156  0.03156
LEN    0.1858      0.1858   0.1858
VDI    0.000224    0.000224 0.000224
VS     0.000170    0.000170 0.000170
VE     0.000229    0.000229 0.000229
VDO      0.0         1.0
WSC      0.06        0.20
DDSRT    0.015       0.036
HTIME   10.0       200.0
FE       6.0        15.0
FS       6.0        15.0
FD       1.0      3100.0
TFIN    91.0       121.1
DEVIA    0.01        0.1
```

8.1.2 EXAMPLE OF DESIGN1.DAT

```
   0.008
 200.0       20.0        0.12983
 121.1       25.0       20.0
chichen stew
   0.00        0.00        0.00
   0.4678  1.789E-07
  10.0     121.1         6.1
potato butter
   0.00        0.00        0.00
   0.6588  1.825E-07
  10.0     121.1         6.1
apple dessert
   0.00        0.00        0.00
   0.4687  1.825E-07
  10.0     100.0         3.1
```

```
C     8.3    ONE-TRAY CONCEPT PROGRAM (OP3.F)
C     Main program for
C     the optimization of retortable plastic compartment tray design
C     Ref.: Saguy, I., 1983. Optimization of dynamic systems utilizing the
C     Maximum principle. pp. 321-359. in "Computer-Aided Techniques
C     in Food Technology", ed. I. Saguy, Marcel Dekker, Inc., New York.
C
C ***************************** NOMENCLATURE **********************************
C     F objective function
C     X(1),...., X(NX) an array containing values of the independent variables
C     Y(1),...., Y(NY) an array containing values of the dependent variables
C     P(1),...., P(NP) an array conatining values of the parameters in the
C                      model which may be varied from one optimization run
C                      to the next
C     NX number of independent decision variables
C     NY number of dependent variables
C     NP number of parameters
C     MAXIT maximum allowable number of iterations to be performed
C     NFREQ iteration frequency at which intermediate printing of the current
C           simplex is to be performed to monitor progress toward solution
C     NAMEX name of variable, expressed as five alphanumeric characters
C     XL(I) lower bound on variable (real)
C     XU(I) upper bound on variable (real)
C     X(I) initial value of the variable corresponding to a feasible point
C     NAMEY name of variable, expressed as five alphanumeric characters
C     YL(I) lower bound on variable (real)
C     YU(I) upper bound on variable (real)
C     NAMEP name of parameter, expressed as five alphanumeric characters
C     P(I) value of parameter
C     NAMEF name of objective function, expressed as five alphanumeric characters
C     RDEV allowable relative deviation in objective function value to be
C          used in convergence test ( a value of 0.001 is typical)
C     ADEV allowable absolute deviation in objective function value to be
C          used in convergence test ( a value of 0.001 is typical)
C
C
C ****************************************************************************
C
      DOUBLE PRECISION DSEED
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),XU(12),Y(30),P(1),NIT
      COMMON/COND1/EDGE,G,HEAD,V(3),XLL(3,3)
      COMMON/STORE/ NX,NY,NP,XL(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
      DIMENSION TM1(300),TM2(7),TM3(7),TT1(300),T2(7),T3(7)
      ALPHA=1.3
      BETA=0.5
      GAMMA=0.10
      NMAX1=50
      DSEED=123457.D0
      MAXIT=60
C  ..... READ BASIC DATA FOR OPTIMIZATION RUN .....
   99 CALL OPTRD
      CALL OPTPR(1)
C  ..... USE OLD SIMPLEX OR NOT? .....
      IF(OLD.EQ.'NO')GOTO 200
      NIT=0
      IND=3
      CALL MODEL(IND)
```

```
      KMAX=2*NX
      OPEN(8,FILE='COMP.DAT',STATUS='OLD')
      KCR=KMAX
      IGG=0
  808 KPT=KCR
      IF(KCR.GT.7)KPT=7
      INDEX=IGG*7
      DO 802 I=1,NX
      READ(8,3001)(XX(I,K+INDEX),K=1,KPT)
  802 CONTINUE
      IF(NY)804,804,805
  805 DO 806 I=1,NY
      READ(8,3001)(YY(I,K+INDEX),K=1,KPT)
  806 CONTINUE
  804 READ(8,3001)(FF(K+INDEX),K=1,KPT)
      KCR=KCR-7
      IGG=IGG+1
      IF(KCR)807,807,808
  807 CONTINUE
      IND=2
      GOTO 300
  200 CONTINUE
      DO 100 I=1,NX
  100 XC(I)=X(I)
      NIT=0
      IND=1
      CALL IMTST(N1,1,IFLAG,IND)
      CALL OPTPR(2)
      IND=2
      IF(IFLAG)500,501,500
  501 CONTINUE
C  ..... ESTABLISH INITIAL SIMPLEX .....
      KMAX=2*NX
      K=1
  104 FF(K)=F
      DO 102 I=1,NX
      XX(I,K)=X(I)
  102 CONTINUE
      IF(NY)120,120,121
  121 CONTINUE
      DO 105 I=1,NY
  105 YY(I,K)=Y(I)
  120 CONTINUE
      DO 103 I=1,NX
  103 XC(I)=(XC(I)*(K-1)+X(I))/K
      IF(K-KMAX)110,300,300
  110 K=K+1
      DO 106 I=1,NX
      CALL GGUBS(DSEED,YFL)
  106 X(I)=XL(I)+YFL*(XU(I)-XL(I))
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)502,503,502
  503 CONTINUE
      GOTO 104
C  ..... BEGIN ITERATIVE SEARCH FOR OPTIMUM .....
  300 CONTINUE
C  ..... ESTABLISH COUNTER FOR INTERMEDIATE PRINTING .....
      IF(NFREQ)520,520,508
  520 IPRT=MAXIT+1
      GOTO 509
  508 IPRT=NFREQ
      WRITE(6,1003)
      CALL OPTPR(3)
```

```
  509 CONTINUE
C  ..... FIND POINTS OF SIMPLEX WITH HIGHEST AND LOWEST FUNCTION VAL. ..
  317 NIT=NIT+1
      FMAX=-1.0E10
      FMIN=1.0E10
      JG=0
      JL=0
      DO 323 J=1,KMAX
      IF(FF(J)-FMAX)301,301,303
  303 JG=J
      FMAX=FF(J)
  301 CONTINUE
      IF(FF(J)-FMIN)322,323,323
  322 FMIN=FF(J)
      JL=J
  323 CONTINUE
C  ..... TEST FOR CONVERGENCE .....
      FDEV=FMAX-FMIN
      FTEST=FDEV-FR*ABS(FMIN)-FA
C  ..... TEST SATISFIED, PROCEDURE HAS CONVERGED .....
      DO 404 I=1,NX
      X(I)=XX(I,JL)
  404 CONTINUE
      IF(NY)407,407,406
  406 DO 405 I=1,NY
  405 Y(I)=YY(I,JL)
  407 CONTINUE
      F=FF(JL)
      IF(FTEST)400,400,401
  400 CALL OPTPR(2)
      GO TO 518
C  ..... TEST NOT SATISFIED, PROCEED FOR ANOTHER ITERATION .....
  401 CONTINUE
C
C     COMPARE CHANGES IN THE OBJECTIVE FUNCTION BETWEEN ITERATIONS
C     TO AVOID UNNESSARY COMPUTATIONS WHEN NOT CONVERGE
C
      EPS = 0.01
      AFD1 = ABS(FTEST-FOLD)
      AFD2 = ABS(FTEST-FNEW)
      IF(AFD1.LE.EPS.OR.AFD2.LE.EPS) GOTO 511
      IF(ABS(FDEV/FMIN).LE.0.01) GOTO 511
  411 FOLD = FNEW
      FNEW = FTEST
C
C     CHECK THE NUMBER OF ITERATIONS AGAINST THE MAXIMUM NUMBER
C
      IF(NIT-MAXIT)402,402,403
C  ..... MAXIMUM ALLOWABLE NO. OF ITERATION HAS BEEN EXCEEDED .....
  403 CALL OPTPR(1)
      WRITE(6,1001)NIT
      DO 704 I=1,NX
      X(I)=XX(I,JL)
  704 CONTINUE
      IF(NY)707,707,706
  706 DO 705 I=1,NY
  705 Y(I)=YY(I,JL)
  707 CONTINUE
      F=FF(JL)
      CALL OPTPR(3)
      CALL OPTPR(2)
      GOTO 511
  402 CONTINUE
```

```
C
C  ..... COMPUTE CENTROID OF POINTS IN SIMPLEX,EXCLUDING ONE
C        WITH HIGHEST FUNCTION VALUE ......
      DO 304 I=1,NX
      XC(I)=0.0
      DO 305 J=1,KMAX
  305 XC(I)=XC(I)+XX(I,J)
  304 XC(I)=(XC(I)-XX(I,JG))/(KMAX-1)
C  ..... COMPUTE NEW TRIAL POINT BY REFLECTING POINT OF HIGHEST
C        FUNCTION VALUE THROUGH CENTROID OF REMAINING POINTS ......
  302 DO 306 I=1,NX
      X(I)=XC(I)-ALPHA*(XX(I,JG)-XC(I))
C  ..... TEST EACH EXPLICIT VARIABLE TO SEE IF IT VIOLATES BOUND.
C        IF SO,SET INSIDE BOUND BY A SMALL AMOUNT .....
      IF(XU(I)-X(I))307,307,308
  307 X(I)=XU(I)-GAMMA*(XU(I)-XC(I))
  308 IF(X(I)-XL(I))309,309,306
  309 X(I)=XL(I)+GAMMA*(XC(I)-XL(I))
  306 CONTINUE
C  ..... TEST TO SEE IF IMPLICIT VARIABLES VIOLATE BOUNDS ......
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)504,505,504
  505 CONTINUE
C  ..... TEST TO SEE IF TRIAL POINT PRODUCES HIGHEST FUNCTION
C        VALUE IN NEW SIMPLEX ......
      DO 312 J=1,KMAX
      IF(J-JG)316,312,316
  316 IF(FF(J)-F)312,312,313
  312 CONTINUE
C  ..... BECAUSE TRIAL POINT PRODUCES HIGHEST FUNCTION VALUE,MOVE
C        TO FRACTIONAL DISTANCE BETA FROM CENTROID OF OTHER POINTS ......
      DO 314 I=1,NX
  314 X(I)=XC(I)+BETA*(X(I)-XC(I))
C  ..... INSERT TRIAL POINT INTO NEW SIMPLEX ......
  313 CONTINUE
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)506,507,506
  507 CONTINUE
      DO 315 I=1,NX
  315 XX(I,JG)=X(I)
      IF(NY)320,320,321
  321 CONTINUE
      DO 318 I=1,NY
  318 YY(I,JG)=Y(I)
  320 CONTINUE
      FF(JG)=F
C  ..... DO INTERMEDIATE PRINTING IF REQUIRED ......
      IF(NIT-IPRT)317,510,510
  510 CALL OPTPR(4)
      CALL OPTPR(3)
      IPRT=IPRT+NFREQ
      GOTO 317
C  ..... PRINT ERROR MESSAGE AFTER CONSTRAINT VIOLATION IN IMTST ......
  500 WRITE(6,1002)
      GOTO 555
  502 CALL FAIL(1)
      GOTO 555
  504 CALL FAIL(2)
      GOTO 555
  506 CALL FAIL(3)
      GOTO 555
  511 WRITE(6,1004) NIT
      WRITE(6,1001) NIT
```

```
      CALL OPTPR(3)
      CALL OPTPR(2)
      GO TO 519
C
C     PRINT TEMPERATURE HISTORY FOR CURRENT TRAY DESIGN
C
  518 CALL OPTPR(1)
      WRITE(6,1000)NIT
  519 WRITE(6,1005)
      T0 = TI
      T1 = TR
      TW = TC
      TMG = THEAT1
      DO 527 K = 1,3
      CALL HEAT(HJ(K),FH(K),T0,T1,-1.,TMG,251,DEL,TM1,TT1)
      TG = TT1(251)
      CALL COOL(CJ(K),C(K),TL,TG,TW,TM2,T2)
  521 CALL COOLA(CJ(K),C(K),TL,TG,TW,TM3,T3,Z)
      DO 523 K1 = 11,251,10
  523 WRITE(6,1006) TM1(K1), TT1(K1)
      DO 525 K2 = 1,7
      TIME2 = TM1(251) + TM2(K2)
  525 WRITE(6,1006) TIME2, T2(K2)
      DO 527 K3 = 1,7
      TIME3 = TM1(251) + TM2(7) + TM3(K3)
      WRITE(6,1006) TIME3, T3(K3)
  527 CONTINUE
C
C     CALCULATE & PRINT THE DIMENSIONS OF THE TRAY
C
C      DO 612 I=1,3
C     XLL(I,3) = (X(2) - HEAD)/2.
C 612 CONTINUE
C      XLL(3,3) = (X(2) - HEAD - 2.*X(1))/2.
C     XLL(1,1) = X(3)/2.
C     XLL(1,2) = X(6)/(4.*XLL(1,1)*XLL(1,3)) / 2.
C     CHECK = 0.3 * XLL(1,1)
C     IF(XLL(1,2).GE.CHECK) THEN
C     GOTO 614
C     ELSE
C     XLL(1,1) = SQRT(X(6)/(8.*0.3*XLL(1,3)))
C     XLL(1,2) = 0.3 * XLL(1,1)
C     ENDIF
C 614 AREA2 = X(5) / (2.*XLL(2,3))
C     AREA3 = X(4) / (2.*XLL(3,3))
C     A = 4.*(XLL(1,1)-0.004-EDGE)
C     B = -4.*EDGE*(XLL(1,1)-0.004-EDGE)-AREA2-AREA3
C     C1 = EDGE * AREA2
C     root = SQRT(B*B - 4.*A*C1)
C     XLL(2,2) = (-1.*B + root) / (2.*A)
C     XLL(2,1) = (X(5)/(4.*XLL(2,2)*XLL(2,3)))/2.
C     XLL(3,2) = XLL(2,2) - EDGE
C     XLL(3,1) = XLL(1,1) - XLL(2,1) - 0.004 - EDGE
      DO 529 I = 1,3
      DO 529 J = 1,3
      XLL(I,J) = 2.0 * XLL(I,J)
  529 CONTINUE
C      XLL(3,3) = X(2) - 2.*X(1)
C     XLL(1,1) = 2. * XLL(1,1)
C     XLL(1,2) = 2. * XLL(1,2)
C     XLL(2,1) = 2. * XLL(2,1)
C     XLL(2,2) = 2. * XLL(2,2)
C     XLL(3,1) = 2. * XLL(3,1)
```

```
C       XLL(3,2) = 2. * XLL(3,2)
        XDO = XLL(3,1) + 2.*EDGE
        YDO = XLL(3,2) + 2.*EDGE
        ZDO = XLL(3,3)
        VDO = XDO * YDO * ZDO
        WRITE(*,*) '     '
        WRITE(*,*) 'ENTREE COMPARTMENT DIMENSION', (XLL(1,I),I=1,3)
        WRITE(*,*) 'STARCH COMPARTMENT DIMENSION', (XLL(2,I),I=1,3)
        WRITE(*,*) 'DESSERT COMPARTMENT DIMENSION', (XDO,YDO,ZDO)
        WRITE(*,*) 'DIMENSION OF INNER DESSERT TRAY', (XLL(3,I),I=1,3)
        WRITE(*,*) 'VOLUME OF (OUTER) DESSERT COMPARTMENT',VDO
  555   STOP
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(/' ','PROCEDURE HAS CONVERGED IN',I4,' ITERATIONS.'/
     *' THE SOLUTION IS AS FOLLOWS:')
 1001 FORMAT(/' ','PROCEDURE HAS NOT CONVERGED IN',I4,' ITERATIONS.'/
     *' ','THE CURRENT TRIAL SOLUTION AND SIMPLEX IS AS FOLLOWS:')
 1002 FORMAT(/' ','BASE SET OF VARIABLES VIOLATES SOME CONSTRAINT.')
 1003 FORMAT(/' ','ITERATION  0')
 1004 FORMAT(/' ','NOT MUCH IMPROVEMENT COULD BE ACHIEVED AFTER ',
     *,I4,'th ITERATION.')
 1005 FORMAT(//' ',5X,'AT TIME = min.',5X,'TEMP. = DEG. C.')
 1006 FORMAT(' ',5X,F15.3,5X,F15.3)
 3001 FORMAT(6X,7E15.5)
        END
C
C       Read input data for main optimization program
C ---------------------------------------------------------------
        SUBROUTINE OPTRD
C ---------------------------------------------------------------
        CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
        COMMON/OPT/ F,X(12),XU(12),Y(30),P(1),NIT
        COMMON/STORE/ NX,NY,NP,XL(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
        COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
C ..... READ BASIC DATA .....
        OPEN(5,FILE='OPT3.DAT',STATUS='OLD')
        READ(5,1000)NTITL,OLD
        READ(5,1001)NX,NY,NP,MAXIT,NFREQ
        DO 100 I=1,NX
  100   READ(5,1002)NAMEX(I),XL(I),XU(I),X(I)
        IF(NY)112,112,113
  113   DO 101 I=1,NY
  101   READ(5,1003)NAMEY(I),YL(I),YU(I)
  112   CONTINUE
        IF(NP)114,114,115
  115   DO 102 I=1,NP
  102   READ(5,1003)NAMEP(I),P(I)
  114   CONTINUE
        READ(5,1003)NAMEF,FR,FA
        CLOSE(5)
        RETURN
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(A47,A3)
 1001 FORMAT(7I5)
 1002 FORMAT(A5,3F10.6)
 1003 FORMAT(A5,3F10.4)
        END
C
C       Print intermediate results and optimal design specifications
C ------------------------------------------------------------------
```

```
      SUBROUTINE OPTPR(IARG)
C ------------------------------------------------------------------
      DIMENSION NINT(50)
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),XU(12),Y(30),P(1),NIT
      COMMON/STORE/ NX,NY,NP,XL(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      DATA NINT/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,
     *22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,
     *43,44,45,46,47,48,49,50/
      GOTO (1,2,3,4,5,6),IARG
    1 CONTINUE
C ..... PRINT TITLE .....
      WRITE(6,2000)NTITL
      RETURN
    2 CONTINUE
C ..... PRINT TRIAL SOLUTION AND LIMITS .....
      WRITE(6,2002)
      WRITE(6,2003)
      DO 200 I=1,NX
  200 WRITE(*,2004)NAMEX(I),XL(I),XU(I),X(I)
      IF(NY)201,201,202
  202 WRITE(6,2005)
      WRITE(6,2003)
      DO 203 I=1,NY
  203 WRITE(6,2004)NAMEY(I),YL(I),YU(I),Y(I)
  201 CONTINUE
      IF(NP)204,204,205
  205 WRITE(6,2011)
      WRITE(6,2012)
      DO 206 I=1,NP
  206 WRITE(6,2004)NAMEP(I),P(I)
  204 CONTINUE
      WRITE(6,2010)
      WRITE(6,2006)
      WRITE(6,2004)NAMEF,F,FR,FA
      RETURN
    3 CONTINUE
C ..... PRINT VALUES OF VARIABLES AT VERTICES OF CURRENT SIMPLEX .....
      KMAX1=KMAX+1
      WRITE(6,2007)KMAX1
C ..... PRINTING DONE IN GROUPS OF SEVEN .....
      KK=1
      KKK=7
  400 CONTINUE
      KKKK=KKK
      IF(KKK.GE.KMAX1)KKK=KMAX1
      IF(KKK.EQ.KMAX1)KKKK=KKK-1
      WRITE(6,2008)(NINT(I),I=KK,KKK)
      DO 301 I=1,NX
      XX(I,KMAX1)=XC(I)
  301 WRITE(6,2004)NAMEX(I),(XX(I,K),K=KK,KKK)
      IF(NY)303,303,304
  304 DO 305 I=1,NY
  305 WRITE(6,2004)NAMEY(I),(YY(I,K),K=KK,KKKK)
  303 CONTINUE
      WRITE(6,2004)NAMEF,(FF(K),K=KK,KKKK)
      IF(KKK.EQ.KMAX1)GOTO 401
      KK=KK+7
      KKK=KKK+7
```

```
      GOTO 400
  401 CONTINUE
      RETURN
    4 CONTINUE
C  ..... PRINT RESULTS AT CURRENT ITERATION .....
      WRITE(*,*) '          '
      WRITE(6,2009)NIT,JG,FDEV,FMIN
      RETURN
    5 CONTINUE
      RETURN
    6 CONTINUE
      RETURN
C  ..... FORMAT STATEMENTS .....
 2000 FORMAT(' ',A47)
 2002 FORMAT(' ','INDEPENDENT VARIABLES')
 2003 FORMAT(' ',1X,'NAME',4X,'LOWER BOUND',4X,'UPPER BOUND',10X,
     *'VALUE'/)
 2004 FORMAT(' ',A5,1P7E15.5)
 2005 FORMAT(' ','DEPENDENT VARIABLES')
 2006 FORMAT(' ',1X,'NAME',10X,'VALUE',8X,'REL DEV',8X,'ABS DEV'/)
 2007 FORMAT(' ','VARIABLES IN SIMPLEX (CENTROID IS VERTEX',I3,')')
 2008 FORMAT(' ','VERTEX',I14,7I15)
 2009 FORMAT(' ','ITERATION',I4,' ENTERING VERTEX',I3,' FDEV =',1PE12.4,
     *' FMIN =',1PE12.4)
 2010 FORMAT(' ','OBJECTIVE FUNCTION')
 2011 FORMAT(' ','PARAMETERS')
 2012 FORMAT(' ',1X,'NAME',10X,'VALUE'/)
      END
C
C     Test for violation of implicit constraints in main program
C  ------------------------------------------------------------------------
      SUBROUTINE IMTST(N,NMAX,IFLAG,IND)
C  ------------------------------------------------------------------------
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),XU(12),Y(30),P(1),NIT
      COMMON/STORE/ NX,NY,NP,XL(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      IFLAG=0
      N=1
C  ..... EVALUATE OBJECTIVE FUNCTION AND DEPENDENT VARIABLES .....
  108 CALL MODEL(IND)
      IF(NY)300,300,301
  300 RETURN
  301 CONTINUE
C  ..... TEST TO SEE IF ANY IMPLICIT CONSTRAINT HAS BEEN VIOLATED .....
      DO 103 I=1,NY
      IF(Y(I)-YL(I))101,102,102
  102 IF(YU(I)-Y(I))101,103,103
  103 CONTINUE
      RETURN
C  ..... BECAUSE TRIAL POINT VIOLATES IMPLICIT CONSTRAINTS, MOVE TO
C        FRACTIONAL DISTANCE BETA FROM CENTROID OF OTHER POINTS .....
  101 DO 104 I=1,NX
  104 X(I)=XC(I)+BETA*(X(I)-XC(I))
      IF(N-NMAX)106,107,107
  106 N=N+1
      GOTO 108
C  ..... TRIAL POINT DID NOT SATISFY IMPLICIT CONSTRAINT AFTER NMAX
C        MOVES TOWARD CENTROID OF OTHER POINTS .....
  107 IFLAG=1
```

```
      RETURN
      END
C
C     Print error messages for main program
C -----------------------------------------------------------------
      SUBROUTINE FAIL(NARG)
C -----------------------------------------------------------------
      WRITE(6,1000)NARG
      CALL OPTPR(2)
      CALL OPTPR(3)
      RETURN
 1000 FORMAT(' ','ERROR ENCOUNTERED IN OPTIMM'/' ','TYPE',I3,
     *' CONSTRAINT VIOLATED')
      END
C
C     Generate random numbers for optimization iterations
C
C -----------------------------------------------------------------
      SUBROUTINE GGUBS (DSEED,R)
C -----------------------------------------------------------------
      REAL R
      DOUBLE PRECISION   DSEED
C                                  SPECIFICATIONS FOR LOCAL VARIABLES
      INTEGER            I
      DOUBLE PRECISION   D2P31M,D2P31
C                                  D2P31M=(2**31) - 1
C                                  D2P31 =(2**31)(OR AN ADJUSTED VALUE)
      DATA               D2P31M/2147483647.D0/
      DATA               D2P31/2147483648.D0/
C                                  FIRST EXECUTABLE STATEMENT
         DSEED = DMOD(16807.D0*DSEED,D2P31M)
      R = DSEED / D2P31
      RETURN
      END
C
C     Estimate thermal processing lethality and time-temperature history
C     for each of the compartments in the tray
C ------------------------------------------------------------------------
      SUBROUTINE MODEL(IND)
C ------------------------------------------------------------------------
      CHARACTER*15 MEAL$(3)
      DIMENSION XL(3),X(4),TTHEAT(3),BI(3),FIMM(3)
      COMMON/OPT/ OBJ,XI(12),XU(12),Y(30),PAR(1),NIT
      COMMON/COND1/EDGE,G,HEAD,V(3),XLL(3,3)
      COMMON/COND/ XKINS,TCOOL,TREF(3),XX(3,3),ZZ(3),FP(3)
     *,XK(3),ALPHA(3),HTA
      COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
C ..... INPUT DATA ......
C XI(1); INSULATION THICKNESS OF DESSERT TRAY
C XI(2); HEIGHT OF THE WHOLE TRAY
C XI(3); LENGTH OF THE ENTREE TRAY
C G; G BETWEEN TRAYS
C V(I); VOLUME OF EACH TRAY (INNER VOLUME)
C XLL(I,J); DIMENSION OF ITH TRAY (INNER)
C
C     CONSTRAINTS FOR TRAY DESIGN
C     LENGTH: <= 11 INCHES
C     DEPTH:  <= 1.1811 INCHES (3 CM)
C     INSULATION THICKNESS: <= 0.6 CM
C     GAP BETWEEN COMPARTMENTS: 0.8 CM
C     WIDTH OF SEALING EDGE: 0.6 CM
```

```
C      HEIGHT OF HEADSPACE: 0.6 CM
C
       IF(IND.EQ.1.OR.IND.EQ.3) GO TO 10
       GO TO 20
   10 OPEN(UNIT=7,FILE='DESIGN1.DAT',STATUS='OLD')
       READ(7,1) G
       READ(7,1) HTA,TCOOL,XKINS
       READ(7,1) TR,TI,TC
       DO 11 I=1,3
       READ(7,2) MEAL$(I)
       READ(7,1) XX(I,1),XX(I,2),XX(I,3)
       READ(7,3) XK(I),ALPHA(I)
   11 READ(7,1) ZZ(I),TREF(I),FP(I)
       CLOSE (UNIT=7)
       WRITE(6,5) (MEAL$(II),II=1,3)
C   ..... CALCULTE THE DIMESION OF THE TRAYS .....
       HEAD = 0.006
       IF(TREF(3).EQ.100.0) THEN
       EDGE = 0.004
       ELSE
       EDGE = 0.0
       XI(1) = 0.0
       ENDIF
       NIT = 0
   20 CONTINUE
C    20 DO 12 I=1,3
C      XLL(I,3) = (XI(2) - HEAD)/2.
C    12 CONTINUE
C       XLL(3,3) = (XI(2) - HEAD - 2.*XI(1))/2.
C      XLL(1,1) = XI(3)/2.
       XLL(1,1) = 0.1858 / 2.
C      XLL(1,2) = XI(6)/(4.*XLL(1,1)*XLL(1,3)) / 2.
       XLL(1,2) = 0.05575 / 2.
C      CHECK = 0.3 * XLL(1,1)
C      IF(XLL(1,2).GE.CHECK) THEN
C      GOTO 14
C      ELSE
C      XLL(1,1) = SQRT(XI(6)/(8.*0.3*XLL(1,3)))
C      XLL(1,2) = 0.3 * XLL(1,1)
C      ENDIF
C    14 AREA2 = XI(5) / (2.*XLL(2,3))
C      AREA3 = XI(4) / (2.*XLL(3,3))
C      A = 4.*(XLL(1,1)-0.004-EDGE)
C      B = -4.*EDGE*(XLL(1,1)-0.004-EDGE)-AREA2-AREA3
C      C1 = EDGE * AREA2
C      root = SQRT(B*B - 4.*A*C1)
C      XLL(2,2) = (-1.*B + root) / (2.*A)
       XLL(2,2) = 0.1203 / 2.
C      XLL(2,1) = (XI(5)/(4.*XLL(2,2)*XLL(2,3)))/2.
       XLL(2,1) = 0.07050 /  2.
       XLL(3,2) = XLL(2,2) - EDGE
C      XLL(3,1) = XLL(1,1) - XLL(2,1) - 0.004 - EDGE
       XLL(3,1) = 0.1073 / 2. - EDGE
C    20 DO 12 I=1,3
C      XLL(I,3) = X(7-I) / (8. * XLL(I,1) * XLL(I,2))
C    12 CONTINUE
       XLL(1,3) = XI(6) / (8. * XLL(1,1) * XLL(1,2))
       XLL(2,3) = XI(5) / (8. * XLL(2,1) * XLL(2,2))
       XLL(3,3) = XI(4) / (8. * XLL(3,1) * XLL(3,2))
       Y(1)=4.*XI(2)*(XLL(3,1)+EDGE)*(XLL(3,2)+EDGE)
       IF(XLL(2,2).LE.0.0.OR.XLL(3,3).LE.0.0) Y(1)=-1000.
       IF(Y(1).LT.0.0) RETURN
       Y(2) = XLL(2,2)*2.
```

```
      Y(3) = XLL(3,3)*2. + HEAD + 2. * XI(1)
C ..... CALCULATE PROCESSING TIME FOR EACH MEAL .....
      T0 = TI
      T1 = TR
      TW = TC
      DO 200 I = 1, 2
      TK=XK(I)
      AL=ALPHA(I)
      Z=ZZ(I)
      TRE=TREF(I)
      DO 100 J=1,3
      XL(J)=XLL(I,J)
      X(J)=XX(I,J)
C     WRITE(6,*) XL(J)
  100 CONTINUE
      HT = HTA
      CALL EIGEN(AL,XL,TK,HT,BI,FH(I),HJ(I))
      CJ(I) = 1.4
      C(I) = FH(I)
      CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,-1.,FP(I),THEAT1,FVALUE
      IF(THEAT1.GE.300.) GO TO 203
      TTHEAT(I)=THEAT1
      FIMM(I)=FVALUE
C     WRITE(6,*) HJ(I),FH(I),TTHEAT(I),FIMM(I)
  200 CONTINUE
      IF(TTHEAT(1).GT.TTHEAT(2)) THEN
      THEAT1=TTHEAT(1)
      FIMAX=FIMM(1)
      IMAX=1
      ELSE
      THEAT1=TTHEAT(2)
      FIMAX=FIMM(2)
      IMAX=2
      ENDIF
  201 Y(4) = THEAT1
  203 DO 207 I = 1,3
      IF(I.EQ.IMAX) GOTO 205
      TK=XK(I)
      AL=ALPHA(I)
      Z=ZZ(I)
      TRE=TREF(I)
      DO 204 J=1,3
      XL(J)=XLL(I,J)
      X(J)=XX(I,J)
  204 CONTINUE
      IF(I.NE.3) THEN
      HT = HTA
      ELSE
      HT=1./(1./HTA+XI(1)/XKINS)
      ENDIF
C
C     ESTIMATE THE STERILIZING VALUES FOR ALL THE FOODS BASED ON THE
C     PROCESSING TIME THEAT1 FOR THE FOOD WHICH IS LEAST OVER-PROCESSED.
C
      CALL EIGEN(AL,XL,TK,HT,BI,FH(I),HJ(I))
      CJ(I) = 1.4
      C(I) = FH(I)
      CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,THEAT1,-1.,-1.,FVALUE)
      Y(I+4) = FVALUE
      Y(8) = T(251)
      GO TO 207
  205 Y(I+4) = FIMAX
  207 CONTINUE
```

```
      OBJ=ABS(Y(5)-FP(1))+ABS(Y(6)-FP(2))+ABS(Y(7)-FP(3))
  208 CONTINUE
      RETURN
C  ..... FORMAT STATEMENTS .....
    1 FORMAT(4F10.5)
    2 FORMAT(A10)
    3 FORMAT(F10.4,E10.4)
    5 FORMAT(' MEAL NAMES ARE ',3(A7,2X))
      END
C  ------------------------------------------------------------------
C     Calculate f and j values for each meal in the compartment tray
C  ------------------------------------------------------------------
      SUBROUTINE EIGEN(AL,XL,TK,HT,BI,FHI,HJI)
C  ------------------------------------------------------------------
      DIMENSION BI(3),XL(3),BETA1(3),FI(3),XJI(3)
      COMMON/THISTORY/ TRE
      FNF(X,BI1)=X*TAN(X)-BI1
      DO 1240 I=1,3
      BI(I)=HT*XL(I)/TK
      BETA1(I) = 0.0
      STP=3.141592654
      STP1=0.001
      STP2=3.141592654/2.-0.001
      XCRIT=0.00001
      FCRIT=0.0001
      IF(BI(I).EQ.0.0) THEN
      BETA1(I)=0.0
      GO TO 1225
      ELSE
      GO TO 1200
      ENDIF
 1200 X1=STP1
      X2=STP2
      ICOUNT = 1
 1210 F1=FNF(X1,BI(I))
      F2=FNF(X2,BI(I))
 1215 FMULT=F1*F2
      IF(FMULT.GT.0.0) GOTO 1225
C  ..... BISECTIONAL METHOD FOR ESTIMATION OF ROOTS .....
 1000 XERR=ABS(X1-X2)/2.0
      X3=(X1+X2)/2.
      F3=FNF(X3,BI(I))
      IF(I.GT.200) GOTO 1220
      IF(XERR.LT.XCRIT) GO TO 1220
      IF(ABS(F3).LT.FCRIT) GO TO 1220
      IF(F3*F1.LE.0.0) THEN
      X2=X3
      F2=F3
      ELSE
      X1=X3
      F1=F3
      ENDIF
      ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1)BI(I)
      GO TO 1210
 1220 BETA1(I) = X3
      GO TO 1230
 1225 ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1) BI(I)
      X1 = STP + STP1
      X2 = STP + STP2
      F1 = FNF(X1,BI(I))
      F2 = FNF(X2,BI(I))
```

```
      GO TO 1215
 1230 FI(I) = LOG(10.0) *XL(I)*XL(I) / (BETA1(I)*BETA1(I)*AL) / 60.
      XJI(I) = 2.0 * SIN(BETA1(I)) / (BETA1(I) +SIN(BETA1(I))*COS(BETA1(I)))
C      WRITE(6,*) BI(I), BETA1(I), XL(I), FI(I), XJI(I)
 1240 CONTINUE
      F = 0.0
      HJI = 1.0
      DO 1260 I1 = 1,3
      F = F + 1.0 / FI(I1)
      HJI = HJI * XJI(I1)
 1260 CONTINUE
      FHI = 1.0 / F
 1280 RETURN
    1 FORMAT(' DONT HAVE ROOT OF TRANSCENDENTAL EQUA.',F12.4)
      END
C
C     ESTIMATE PROPER HEAT PROCESSES OF RETORTABLE PLASTIC PACKAGE
C     FOR MULTIPLE FOODS. DEVELOPED MAINLY BASED ON THE PROGRAMS BY
C     DR. K. HAYAKAWA,
C     ADVANCES IN FOOD RESEARCH, VOL. XX. PP. 75-141, 1977.
C     THIS SUBROUTINE SOLVES 2 TYPES OF PROBLEMS. THEY INCLUDE:
C       TYPE B: GIVEN Fp, Solve for tb (thermal processing time)
C       TYPE A: GIVEN tb, Calculate the equivalent Fp
C
C ******************************** NOMENCLATURE **********************************
C     C    Slope index of cooling curve
C     CJ   Intercept coefficient of cooling curve
C     FH   Slope index of heating curve
C     HJ   Intercept coefficient of heating curve
C     FP1  Target sterilizing value
C     FPP  Estimated sterilizing value for given TG or TMG
C     T0   Initial temperature of food (Deg. C.)
C     T1   Holding temperature heating medium (Deg. C.)
C     TANS Length of heating phase to be estimated. A thermal process with TANS
C          minutes of processing time produces a target sterilizing value FP1
C     TG   Food temperature at end of heating phase of thermal process.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TG = - 1.0.
C     TMG  Length of heating phase.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TMG = -1.0
C     TW   Cooling medium temperature (Deg. C.)
C *****************************************************************************
C
C  ----------------------------------------------------------------------
      SUBROUTINE PROCESS(T0,T1,TW,HJ,FH,CJ,C,Z,TG,TMG,FP1,TANS,FPP)
C  ----------------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
      ABC(1)=-1.0
      ABC(2)=-0.8302239
      ABC(3)=-0.4688488
      ABC(4)=0.0
      ABC(5)=0.4688488
      ABC(6)=0.8302239
      ABC(7)=1.0
      H(1)=0.0476190
      H(2)=0.2768260
      H(3)=0.4317454
      H(4)=0.4876190
      H(5)=0.4317454
```

```
      H(6)=0.2768260
      H(7)=0.0476190
      DO 141 J=1,300
      T(J)=0.
  141 TM(J)=0.
      FPP=0.
      YFP = 0.
      YFP1 = 0.
      YFP2 = 0.
      TANS=0.
      IF(FP1.LE.0.) GO TO 146
C
C     This is a Type B Problem.
C     It solves for the processing time TANS to achieve target Fp.
C
      TMG1 = FP1
      FPP = 0.
      TMG2 = 40. * FP1
  142 TMG = TMG1
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
C     WRITE(6,*)hj,fh,t0,t1,TMG,DEL,TM(251),T(251)
      CALL SIMP(T,DEL,251,Z,FPH1)
C     WRITE(6,*)T(251),del,z,FPH1
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
C     WRITE(6,*)FPC
      FPP1 = FPH1 + FPC
      YFP1 = FP1 - FPP1
  143 TMG = TMG2
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH2)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP2 = FPH2 + FPC
      YFP2 = FP1 - FPP2
      TMG = (TMG1+TMG2) / 2.0
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP = FPH + FPC
      YFP = FP1 - FPP
C     write(6,*) tmg, fpp
      IF((YFP1*YFP).GT.0..AND.(YFP2*YFP).GT.0.) GOTO 148
      IF(ABS(FPP-FP1).LE.0.1) GO TO 144
      YCHECK = YFP1 * YFP
      IF(YCHECK.LE.0.0) THEN
      TMG2 = TMG
      GO TO 143
      ELSE
      TMG1 = TMG
      GO TO 142
      ENDIF
  144 TANS = TMG
      GO TO 150
C
C     This is a type A problem.
C     Given heating time, solve for actual Fp.
C
  146 TG = T1 - HJ *(T1-T0) *10.**(-TMG /FH)
      CALL HEAT(HJ,FH,T0,T1,TG,-1.0,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP = FPH + FPC
      GO TO 150
  148 WRITE(6,149)
```

```
  149 FORMAT('     ','PROCESSING TIME IS LARGER THAN 40 Fp.',/,
     *'     ','Please modify the program!')
  150 RETURN
      END
C
C     Calcualte food temperatures on a heating curve
C     The equations were updated (from the 1977 Reference)
C     with reference to Lekwauwa, A. N. and Hayakawa, K., 1986.
C     J. Food Sci. 51(4): 1042-1049, 1056.
C
C ****************************** NOMENCLATURE ***************************
C     DEL  Time increment for heating phase
C     NTRM Number of food temperatures to be estimated. 2 < NTRM <= 300
C     T    Food temperature estimated (Deg. C.)
C     TM   Heating times at which food temperatures reach to T's
C ***********************************************************************
C ------------------------------------------------------------------
      SUBROUTINE HEAT(HJ,FH,T0,T1,TG,TMG,NTRM,DEL,TM,T)
C ------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION T(300),TM(300)
      AN(A,AF,AJ) = (A/AF - ALOG10(AJ)) / (A/AF)
      BA(AJ,A,AF,BN) = A* (A/AF - ALOG10(AJ))**(BN)
      TA(TMA,BAA,AAN)=T1-(T1-T0)*EXP(-2.30259*EXP(ALOG(
     *TMA/BAA)*(1./AAN)))
      TIA(BAA,TP,AAN)=BAA*((ALOG10((T1-T0)/(T1-TP)))**AAN)
      BB(TLB)=(1./TLB)*(ATAN((ALOG10(T1-T0))/(ALOG10(HJ*
     *(T1-T0))-TLB/FH))-0.785398)
      TB(BBB,TMB)=T1-(T1-T0)**(1./TAN(BBB*TMB+0.785398))
      TIB(BBB,TP)=(1./BBB)*(ATAN((ALOG10(T1-T0))/(ALOG10(T1
     *-TP)))-0.785398)
      BC(TLC)=(1./TLC)*ACOS((ALOG10(HJ*(T1-T0))-TLC/FH
     *)/(ALOG10(T1-T0)))
      TC(BCC,TMC)=T1-(T1-T0)**(COS(BCC*TMC))
      TIC(BCC,TP)=(1./BCC)*ACOS((ALOG10(T1-TP))/(ALOG10(T1
     *-T0)))
      TD(TMD)=T1-HJ*(T1-T0)*EXP(-2.30259*(TMD/FH))
      TID(TP)=FH*ALOG10(HJ*(T1-T0)/(T1-TP))
      DO 90 I=1,300
      T(I)=0.0
   90 TM(I)=0.0
      NXX=NTRM-1
      IF(HJ.LT.0.001)GO TO 1
      IF(HJ.LT.0.40)GO TO 2
      IF(HJ.LE.0.999999)GO TO 3
      IF(HJ.LE.1.00001)GO TO 7
      IF(HJ.GT.6500.0)GO TO 4
      GO TO 6
    1 WRITE(*,5)
    5 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH < 0.001')
    2 TL = FH * (0.3913 - 0.3737 * ALOG10(HJ))
      RN = AN(TL,FH,HJ)
      B = BA(HJ,TL,FH,RN)
      IF(TG.LT.0.0)GO TO 8
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 9
      TMH=TID(TG)
      TH=TG
      GO TO 10
    9 TMH=TIA(B,TG,RN)
      TH=TG
      GO TO 10
```

```
    8 IF(TMG.LT.TL)GO TO 11
      TH=TD(TMG)
      TMH=TMG
      GO TO 10
   11 TH=TA(TMG,B,RN)
      TMH=TMG
   10 T(1)=T0
      TM(1)=0.
      DEL=TMH/NXX
      T(NTRM)=TH
      TM(NTRM)=TMH
      DO 100 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 102
      T(I)=TA(TMI,B,RN)
      GO TO 100
  102 T(I)=TD(TMI)
  100 CONTINUE
      GO TO 60
    3 TL = 0.9*FH*(1.-HJ)
      B = BB(TL)
      IF(TG.LT.0.0)GO TO 19
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 20
      TMH=TID(TG)
      TH=TG
      GO TO 21
   20 TMH=TIB(B,TG)
      TH=TG
      GO TO 21
   19 IF(TMG.LT.TL)GO TO 22
      TH=TD(TMG)
      TMH=TMG
      GO TO 21
   22 TH=TB(B,TMG)
      TMH=TMG
   21 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 30 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 32
      T(I)=TB(B,TMI)
      GO TO 30
   32 T(I)=TD(TMI)
   30 CONTINUE
      GO TO 60
    7 IF(TG.LT.0.0)GO TO 34
      TMH=TID(TG)
      TH=TG
      GO TO 35
   34 TH=TD(TMG)
      TMH=TMG
   35 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 40 I=2,NXX
```

```
      TMI=DEL*(I-1)
      TM(I)=TMI
      T(I)=TD(TMI)
   40 CONTINUE
      GO TO 60
    4 WRITE(*,43)
   43 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH > 6500.0')
    6 IF(HJ.LE.5.8) TL = 0.7*FH*(HJ-1.)
      IF(HJ.GT.5.8) TL = 1.54 *FH *ALOG10(HJ/1.8)
      B = BC(TL)
      IF(TG.LT.0.0)GO TO 44
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 45
      TMH=TID(TG)
      TH=TG
      GO TO 46
   45 TMH=TIC(B,TG)
      TH=TG
      GO TO 46
   44 IF(TMG.LT.TL)GO TO 47
      TH=TD(TMG)
      TMH=TMG
      GO TO 46
   47 TH=TC(B,TMG)
      TMH=TMG
   46 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 55 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 57
      T(I)=TC(B,TMI)
      GO TO 55
   57 T(I)=TD(TMI)
   55 CONTINUE
   60 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM TWO FOOD TEMPERATURES
C     DEL MINUTE APART from each other DURING THE HEATING PHASE
C
C ******************************  NOMENCLATURE ******************************
C     DELF Estimated sterilizing value (min.)
C     TH Food temperature (TH > TL)
C     TL Food temperature (TL < TH)
C     Z  Slope index of thermal death time curve (C. Deg.)
C ***************************************************************************
C ----------------------------------------------------------------
      SUBROUTINE FDIF(DELF,T1,TH,TL,DEL,Z)
C ----------------------------------------------------------------
      TM=FTG(T1,TH,TL,0.5*DEL,0.,DEL)
      DELF=DEL/6.0*(RT(TL,Z)+4.*RT(TM,Z)+RT(TH,Z))
      RETURN
      END
C ----------------------------------------------------------------
      FUNCTION RT(T,Z)
C ----------------------------------------------------------------
      COMMON/THISTORY/ TRE
      IF(ABS(T-TRE).LT.1.E-5)GO TO 1
```

```
      TRAT=(T-TRE)/2
      IF(TRAT.LT.-6.0)GO TO 3
      RT=10.**TRAT
      GO TO 2
    3 RT=1.0E-6
      GO TO 2
    1 RT=1.0
    2 RETURN
      END
C   ------------------------------------------------------------
      FUNCTION FX(FA,FB,TA,TB,TX)
C   ------------------------------------------------------------
      FX=FA+(TX-TA)*(FB-FA)/(TB-TA)
      RETURN
      END
C   ------------------------------------------------------------
      FUNCTION FTG(T1,TH,TL,TMG,TML,DEL)
C   ------------------------------------------------------------
      IF(ABS(TMG-TML).LE.1.E-5)GO TO 1
      IF(ABS(T1-TH).LE.1.E-5)GO TO 2
      R=(T1-TH)/(T1-TL)
      IF(R.GE.0.9999)GO TO 2
      FTG=T1-(T1-TL)*R**((TMG-TML)/DEL)
      GO TO 3
    1 FTG=TL
      GO TO 3
    2 FTG=(TH+TL)/2.
    3 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM A COOLING CURVE
C
C ******************************  NOMENCLATURE  ****************************
C     FPC Estimated sterilizing value (min.) during cooling phase
C **************************************************************************
C   ------------------------------------------------------------------------
      SUBROUTINE FCOL(FPC,CJ,C,TG,TW,Z)
C   ------------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      DIMENSION TMC(7),TC(7)
      DO 1 I=1,7
      TMC(I)=0.
    1 TC(I)=0.
      IF(ABS(CJ-1.0).LT.1.0E-4)GO TO 2
      CALL COOL(CJ,C,TL,TG,TW,TMC,TC)
      CALL RATE(FPA,TC,Z,0.,TL)
      GO TO 3
    2 FPA=0.
      TL=0.
    3 CALL COOLA(CJ,C,TL,TG,TW,TMC,TC,Z)
      CALL RATE(FPB,TC,Z,TL,TMC(7))
      FPC=FPA+FPB
      RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM DATA ON FOOD
C     TEMPERATURE COLLECTED AT UNIFORM TIME INTERVALS
C
C ******************************  NOMENCLATURE  ****************************
C     DELX uniform time interval (min.)
C     NO   Number of temperature data collected
```

```
C     Y    Vector of temperature data (Deg. C.)
C *********************************************************************
C  ------------------------------------------------------------------
      SUBROUTINE SIMP(Y,DELX,N0,Z,FP)
C  ------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION Y(300)
      NN=N0/2
      NM=NN*2
      IF(NM.EQ.N0)GO TO 10
      NM=N0
      GO TO 11
   10 NM=N0-1
   11 IF(N0-3)1,2,3
    1 IF(N0.EQ.2)GO TO 12
      IF(N0.EQ.1)GO TO 13
      WRITE(*,14)
   14 FORMAT(' ','NO FP IS ESTIMATED SINCE N0 < 1 AT SUBROUTINE SIMP')
   13 FP=0.
      GO TO 6
    2 FP=DELX/3.*(RT(Y(1),Z)+4.*RT(Y(2),Z)+RT(Y(3),Z))
      GO TO 6
    3 FP=RT(Y(1),Z)+RT(Y(NM),Z)
      M=NM-1
      FPA=0.
      DO 4 I=2,M,2
    4 FPA=FPA+RT(Y(I),Z)
      IF(N0.EQ.4)GO TO 15
      FPB=0.
      M=NM-2
      DO 5 I=3,M,2
    5 FPB=FPB+RT(Y(I),Z)
      GO TO 16
   15 FP=DELX/3.*(FP+4.*FPA)
      GO TO 20
   16 FP=DELX/3.*(FP+4.*FPA+2.*FPB)
      IF(NM.EQ.N0)GO TO 6
   20 FP=FP+DELX/2.*(RT(Y(N0-1),Z)+RT(Y(N0),Z))
      GO TO 6
   12 FP=DELX/2.*(RT(Y(1),Z)+RT(Y(2),Z))
    6 RETURN
      END
C
C     CALCULATE 7 TEMPERATURES ON A CURVILINEAR PORTION OF
C     A COOLING CURVE. THESE TEMPERATURES ARE THEN USED TO
C     CALCULATE A STERILIZING VALUE BY USING THE 7 POINT
C     LOBBATO QUADRATURE FORMULA.
C
C ******************************** NOMENCLATURE ************************
C     FC     Slope index of cooling curve
C *********************************************************************
C  ------------------------------------------------------------------
      SUBROUTINE COOL(CJ,FC,TL,TG,TW,TM,T)
C  ------------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      DIMENSION TM(7),T(7)
      TXA(Y,BY,YN)=TW+(TG-TW)*EXP(-2.302585*EXP(ALOG(Y/BY)*(1./YN)))
      TXB(Y,BY)=TW+(TG-TW)**(1./TAN(BY*Y+0.785398))
      TXC(Y,BY)=TW+(TG-TW)**(COS(BY*Y))
      TMX(X,TK)=TK/2.+TK*X/2.
      DO 50 I=1,7
      TM(I)=0.
```

```
   50 T(I)=0.
      IF(CJ.GE.0.001)GO TO 11
   10 WRITE(*,12)
   12 FORMAT(1X,'TM & T VLAUES ESTIMATED BY SUBROUTINE COOL ARE QUESTI
     *ONABLE SINCE CJ < 0.001')
      GO TO 13
   11 IF(CJ.LE.0.4)GO TO 13
      IF(CJ.LE.0.999999)GO TO 14
      IF(CJ.LE.1.00001)GO TO 15
      IF(CJ.LE.6500.0)GO TO 16
      WRITE(*,17)
   17 FORMAT(1X,'TM & T VALUES ESTIMATED BY COOL ARE QUESTION
     *ABLE SINCE CJ > 6500.0')
      GO TO 16
   13 TL = FC * (0.3913 - 0.3737 * ALOG10(CJ))
      EN = (TL/CJ - ALOG10(CJ)) / (TL/CJ)
      B = TL * (TL/CJ - ALOG10(CJ))**(EN)
      T(1)=TG
      TM(1)=0.
      DO 18 I=2,7
      IF(I.EQ.4)GO TO 19
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   20 TXT=TXA(TM(I),B,EN)
      T(I)=TXT
      GO TO 18
   19 TM(I)=TL/2.
      GO TO 20
   18 CONTINUE
      GO TO 8
   15 WRITE(*,21)
   21 FORMAT(1X,'CALLING EXIT FROM COOL SINCE CJ=1.0')
      GO TO 8
   14 TL=0.9*FC*(1.-CJ)
      B=(1./TL)*(ATAN(ALOG10(TG-TW)/(ALOG10(CJ*(TG-TW))-TL/FC))-
     *0.7853982)
      TM(1)=0.
      T(1)=TG
      DO 22 I=2,7
      IF(I.EQ.4)GO TO 23
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   24 TXT=TXB(TM(I),B)
      T(I)=TXT
      GO TO 22
   23 TM(I)=TL/2.
      GO TO 24
   22 CONTINUE
      GO TO 8
   16 IF(CJ.LE.5.8) TL=0.7*FC*(CJ-1.)
      IF(CJ.GT.5.8) TL = 1.54 *FC *ALOG10(CJ/1.8)
      B=(1.0/TL)*ACOS((ALOG10(CJ*(TG-TW))-TL/FC)/ALOG10(TG-TW))
      TM(1)=0.
      T(1)=TG
      DO 25 I=2,7
      IF(I.EQ.4)GO TO 26
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   27 TXT=TXC(TM(I),B)
      T(I)=TXT
      GO TO 25
   26 TM(I)=TL/2.
      GO TO 27
```

```
   25 CONTINUE
    8 RETURN
      END
C
C     CALCULATE 7 TEMPERATURES ON A LINEAR PORTION
C     OF A COOLING CURVE
C ------------------------------------------------------------------
      SUBROUTINE COOLA(CJ,FC,TL,TG,TW,TM,T,Z)
C ------------------------------------------------------------------
      DIMENSION TM(7),T(7)
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      TX(Y)=TW+CJ*(TG-TW)*EXP(-2.302585*Y/FC)
      TMX(X,TBX,TIN)=(TBX+TIN)/2.+(TBX-TIN)*X/2.
      TMY(X,TBX)=TBX/2.+TBX*X/2.
      TIM(X)=FC*ALOG10(CJ*(TG-TW)/(X-TW))
      DO 50 I=1,7
      TM(I)=0.0
   50 T(I)=0.0
      IF(CJ.LE.0.999999)GO TO 8
      IF(CJ.LE.1.00001)GO TO 9
      GO TO 8
    9 TBL=TG
C .....WHEN CJ=1.0,THE COMPUTATIONAL FLOW IS BLANCHED TO 9. IN
C      THIS CASE TBL=TG SINCE THERE IS NO CURVELINEAR PORTION.....
      GO TO 10
    8 TBL=TX(TL)
   10 IF(TRE.NE.(5.*Z))GO TO 20
      TLOW=1.E-6
      GO TO 21
   20 TLOW=TRE - 5.*Z
   21 IF(TLOW.GE.TG)GO TO 1
      IF(TLOW.GE.TBL)GO TO 1
      IF(TLOW.GT.TW)GO TO 2
      IF(TLOW.LE.TW)GO TO 3
    1 TEND=TIM((TBL+TW)/2.)
    7 CONTINUE
      T(1)=TBL
      TM(1)=TL
      DO 4 I=2,7
      IF(I.EQ.4)GO TO 5
      IF(CJ.LE.0.999999)GO TO 11
      IF(CJ.LE.1.00001)GO TO 12
   11 TMT=TMX(ABC(I),TEND,TL)
    6 TM(I)=TMT
      GO TO 13
   12 TMT=TMY(ABC(I),TEND)
      GO TO 6
   13 T(I)=TX(TMT)
      GO TO 4
    5 IF(CJ.LE.0.999999)GO TO 14
      IF(CJ.LE.1.00001)GO TO 15
   14 TMT=(TEND+TL)/2.
      GO TO 6
   15 TMT=TEND/2.
      GO TO 6
    4 CONTINUE
      GO TO 16
    2 TEND=TIM(TLOW)
      GO TO 7
    3 TEND=TIM(TW+0.01*(TBL-TW))
      GO TO 7
   16 RETURN
```

```
      END
C
C     CALCULATE STERILIZING VALUES BY
C     APPLYING LOBBATO 7 POINT QUADRATURE FORMULA
C
C ****************************** NOMENCLATURE ***************************
C     R     Sterilizing value calculated (min.)
C     T     Seven temperatures (Deg. C.) used to calculate R value.
C     TBGIN Lower time limit of integration (min.)
C     TEND  Upper time limit of integration (min.)
C ***********************************************************************
C ------------------------------------------------------------
      SUBROUTINE RATE(R,T,Z,TBGIN,TEND)
C ------------------------------------------------------------
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      DIMENSION T(7)
      IF(T(1).NE.TRE)GO TO 2
      RA=H(1)
      GO TO 4
    2 RA=H(1)*10.**((T(1)-TRE)/Z)
    4 CONTINUE
      DO 1 I=2,7
      IF(T(I).NE.TRE)GO TO 5
      RA=RA+H(I)
      GO TO 1
    5 RA=RA+H(I)*10.**((T(I)-TRE)/Z)
    1 CONTINUE
      IF(TBGIN.GE.1.0E-3)GO TO 6
      R=TEND/2.*RA
      GO TO 7
    6 R=(TEND-TBGIN)/2.*RA
    7 RETURN
      END
```

Dimension Design Program

```
C      9.3    DIMESION DESIGN PROGRAM (OP2.F)
C      Main program for
C      the optimization of retortable plastic compartment tray design
C      Ref.: Saguy, I., 1983. Optimizetion of dynamic systems utilizing the
C      Maximum principle. pp. 321-359. in "Computer-Aided Techniques
C      in Food Technology", ed. I. Saguy, Marcel Dekker, Inc., New York.
C
C ***************************** NOMENCLATURE *********************************
C      F objective function
C      X(1),..., X(NX) an array conteining values of the independent variables
C      Y(1),..., Y(NY) an array containing values of the dependent variables
C      P(1),..., P(NP) an array conatining values of the parameters in the
C                      model which may be veried from one optimization run
C                      to the next
C      NX number of independent decision variables
C      NY number of dependent variables
C      NP number of parameters
C      MAXIT maximum allowable number of iterations to be performed
C      NFREQ iteration frequency et which intermediate printing of the current
C            simplex is to be performed to monitor progress toward solution
C      NAMEX name of variable, expressed es five alphanumeric characters
C      XL(I) lower bound on variable (real)
C      XU(I) upper bound on variable (real)
C      X(I) initial value of the variable corresponding to a feasible point
C      NAMEY name of variable, expressed es five elphanumeric characters
C      YL(I) lower bound on variable (real)
C      YU(I) upper bound on variable (real)
C      NAMEP name of parameter, expressed es five alphanumeric characters
C      P(I) value of parameter
C      NAMEF name of objective function, expressed as five alphanumeric characters
C      RDEV allowable relative deviation in objective function value to be
C           used in convergence test ( a value of 0.001 is typical)
C      ADEV allowable absolute deviation in objective function velue to be
C           used in convergence test ( a value of 0.001 is typical)
C
C
C ****************************************************************************
C
      DOUBLE PRECISION DSEED
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/COND1/FLANGE,G,HEAD,V(3),XLL(3,3)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
      DIMENSION TM1(300),TM2(7),TM3(7),TT1(300),T2(7),T3(7)
      ALPHA=1.3
      BETA=0.5
      GAMMA=0.10
      NMAX1=50
      DSEED=123457.D0
      MAXIT=100
C ..... READ BASIC DATA FOR OPTIMIZATION RUN .....
   99 CALL OPTRD
      CALL OPTPR(1)
C ..... USE OLD SIMPLEX OR NOT? .....
      IF(OLD.EQ.'NO')GOTO 200
      NIT=0
      IND=3
      CALL MODEL(IND)
```

```
      KMAX=2*NX
      OPEN(8,FILE='COMP.DAT',STATUS='OLD')
      KCR=KMAX
      IGG=0
  808 KPT=KCR
      IF(KCR.GT.7)KPT=7
      INDEX=IGG*7
      DO 802 I=1,NX
      READ(8,3001)(XX(I,K+INDEX),K=1,KPT)
  802 CONTINUE
      IF(NY)804,804,805
  805 DO 806 I=1,NY
      READ(8,3001)(YY(I,K+INDEX),K=1,KPT)
  806 CONTINUE
  804 READ(8,3001)(FF(K+INDEX),K=1,KPT)
      KCR=KCR-7
      IGG=IGG+1
      IF(KCR)807,807,808
  807 CONTINUE
      IND=2
      GOTO 300
  200 CONTINUE
      DO 100 I=1,NX
  100 XC(I)=X(I)
      NIT=0
      IND=1
      CALL IMTST(N1,1,IFLAG,IND)
      CALL OPTPR(2)
      IND=2
      IF(IFLAG)500,501,500
  501 CONTINUE
C  ..... ESTABLISH INITIAL SIMPLEX .....
      KMAX=2*NX
      K=1
  104 FF(K)=F
      DO 102 I=1,NX
      XX(I,K)=X(I)
  102 CONTINUE
      IF(NY)120,120,121
  121 CONTINUE
      DO 105 I=1,NY
  105 YY(I,K)=Y(I)
  120 CONTINUE
      DO 103 I=1,NX
  103 XC(I)=(XC(I)*(K-1)+X(I))/K
      IF(K-KMAX)110,300,300
  110 K=K+1
      DO 106 I=1,NX
      CALL GGUBS(DSEED,YFL)
  106 X(I)=XL(I)+YFL*(XU(I)-XL(I))
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)502,503,502
  503 CONTINUE
      GOTO 104
C  ..... BEGIN ITERATIVE SEARCH FOR OPTIMUM .....
  300 CONTINUE
C  ..... ESTABLISH COUNTER FOR INTERMEDIATE PRINTING .....
      IF(NFREQ)520,520,508
  520 IPRT=MAXIT+1
      GOTO 509
  508 IPRT=NFREQ
      WRITE(6,1003)
      CALL OPTPR(3)
```

```
  509 CONTINUE
C ..... FIND POINTS OF SIMPLEX WITH HIGHEST AND LOWEST FUNCTION VAL. ..
  317 NIT=NIT+1
      FMAX=-1.0E10
      FMIN=1.0E10
      JG=0
      JL=0
      DO 323 J=1,KMAX
      IF(FF(J)-FMAX)301,301,303
  303 JG=J
      FMAX=FF(J)
  301 CONTINUE
      IF(FF(J)-FMIN)322,323,323
  322 FMIN=FF(J)
      JL=J
  323 CONTINUE
C ..... TEST FOR CONVERGENCE .....
      FDEV=FMAX-FMIN
      FTEST=FDEV-FR*ABS(FMIN)-FA
      IF(FTEST)400,400,401
C ..... TEST SATISFIED, PROCEDURE HAS CONVERGED .....
  400 CALL OPTPR(1)
      WRITE(6,1000)NIT
      DO 404 I=1,NX
      X(I)=XX(I,JL)
  404 CONTINUE
      IF(NY)407,407,406
  406 DO 405 I=1,NY
  405 Y(I)=YY(I,JL)
  407 CONTINUE
      F=FF(JL)
      CALL OPTPR(2)
      GOTO 519
C ..... TEST NOT SATISFIED, PROCEED FOR ANOTHER ITERATION .....
  401 CONTINUE
C
C     COMPARE CHANGES IN THE OBJECTIVE FUNCTION BETWEEN ITERATIONS
C     TO AVOID UNNESSARY COMPUTATIONS WHEN NOT CONVERGE
C
      EPS = 0.001
      AFD1 = ABS(FDEV-FOLD)
      AFD2 = ABS(FDEV-FNEW)
      IF(AFD1.GT.EPS.OR.AFD2.GT.EPS) GOTO 411
      IF(ABS(FDEV/FMIN).LE.0.1) GOTO 511
  411 FOLD = FNEW
      FNEW = FDEV
C
C     CHECK THE NUMBER OF ITERATIONS AGAINST THE MAXIMUM NUMBER
C
      IF(NIT-MAXIT)402,402,403
C ..... MAXIMUM ALLOWABLE NO. OF ITERATION HAS BEEN EXCEEDED .....
  403 CALL OPTPR(1)
      WRITE(6,1001)NIT
      DO 704 I=1,NX
      X(I)=XX(I,JL)
  704 CONTINUE
      IF(NY)707,707,706
  706 DO 705 I=1,NY
  705 Y(I)=YY(I,JL)
  707 CONTINUE
      F=FF(JL)
      CALL OPTPR(3)
      CALL OPTPR(2)
```

```
      GOTO 555
  402 CONTINUE
C
C ..... COMPUTE CENTROID OF POINTS IN SIMPLEX,EXCLUDING ONE
C         WITH HIGHEST FUNCTION VALUE .....
      DO 304 I=1,NX
      XC(I)=0.0
      DO 305 J=1,KMAX
  305 XC(I)=XC(I)+XX(I,J)
  304 XC(I)=(XC(I)-XX(I,JG))/(KMAX-1)
C ..... COMPUTE NEW TRIAL POINT BY REFLECTING POINT OF HIGHEST
C         FUNCTION VALUE THROUGH CENTROID OF REMAINING POINTS .....
      DO 306 I=1,NX
      X(I)=XC(I)-ALPHA*(XX(I,JG)-XC(I))
C ..... TEST EACH EXPLICIT VARIABLE TO SEE IF IT VIOLATES BOUND.
C         IF SO,SET INSIDE BOUND BY A SMALL AMOUNT .....
      IF(XU(I)-X(I))307,307,308
  307 X(I)=XU(I)-GAMMA*(XU(I)-XC(I))
  308 IF(X(I)-XL(I))309,309,306
  309 X(I)=XL(I)+GAMMA*(XC(I)-XL(I))
  306 CONTINUE
C ..... TEST TO SEE IF IMPLICIT VARIABLES VIOLATE BOUNDS .....
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)504,505,504
  505 CONTINUE
C ..... TEST TO SEE IF TRIAL POINT PRODUCES HIGHEST FUNCTION
C         VALUE IN NEW SIMPLEX .....
      DO 312 J=1,KMAX
      IF(J-JG)316,312,316
  316 IF(FF(J)-F)312,312,313
  312 CONTINUE
C ..... BECAUSE TRIAL POINT PRODUCES HIGHEST FUNCTION VALUE,MOVE
C         TO FRACTIONAL DISTANCE BETA FROM CENTROID OF OTHER POINTS .....
      DO 314 I=1,NX
  314 X(I)=XC(I)+BETA*(X(I)-XC(I))
C ..... INSERT TRIAL POINT INTO NEW SIMPLEX .....
  313 CONTINUE
      CALL IMTST(N1,NMAX1,IFLAG,IND)
      IF(IFLAG)506,507,506
  507 CONTINUE
      DO 315 I=1,NX
  315 XX(I,JG)=X(I)
      IF(NY)320,320,321
  321 CONTINUE
      DO 318 I=1,NY
  318 YY(I,JG)=Y(I)
  320 CONTINUE
      FF(JG)=F
C ..... DO INTERMEDIATE PRINTING IF REQUIRED .....
      IF(NIT-IPRT)317,510,510
  510 CALL OPTPR(4)
      CALL OPTPR(3)
      IPRT=IPRT+NFREQ
      GOTO 317
C ..... PRINT ERROR MESSAGE AFTER CONSTRAINT VIOLATION IN IMTST .....
  500 WRITE(6,1002)
      GOTO 555
  502 CALL FAIL(1)
      GOTO 555
  504 CALL FAIL(2)
      GOTO 555
  506 CALL FAIL(3)
      GOTO 555
```

```
  511 WRITE(6,1004) NIT
      WRITE(6,1001) NIT
      CALL OPTPR(3)
      CALL OPTPR(2)
C
C     PRINT TEMPERATURE HISTORY FOR CURRENT TRAY DESIGN
C
  519 WRITE(6,1005)
      T0 = TI
      T1 = TR
      TW = TC
      TMG = THEAT1
      DO 527 K = 1,3
      CALL HEAT(HJ(K),FH(K),T0,T1,-1.,TMG,251,DEL,TM1,TT1)
      TG = TT1(251)
      CALL COOL(CJ(K),C(K),TL,TG,TW,TM2,T2)
  521 CALL COOLA(CJ(K),C(K),TL,TG,TW,TM3,T3,Z)
      DO 523 K1 = 11,251,10
  523 WRITE(6,1006) TM1(K1), TT1(K1)
      DO 525 K2 = 1,7
      TIME2 = TM1(251) + TM2(K2)
  525 WRITE(6,1006) TIME2, T2(K2)
      DO 527 K3 = 1,7
      TIME3 = TM1(251) + TM2(7) + TM3(K3)
      WRITE(6,1006) TIME3, T3(K3)
  527 CONTINUE
C
C     CALCULATE & PRINT THE DIMENSIONS OF THE TRAY
C
      DO 529 I = 1,3
      XLL(I,3) = X(2)
  529 CONTINUE
      XLL(3,3) = X(2) - 2.*X(1)
      XLL(1,1) = 2. * XLL(1,1)
      XLL(1,2) = 2. * XLL(1,2)
      XLL(2,1) = 2. * XLL(2,1)
      XLL(2,2) = 2. * XLL(2,2)
      XLL(3,1) = 2. * XLL(3,1)
      XLL(3,2) = 2. * XLL(3,2)
      XDO = XLL(3,1) + 2.*X(1) + 2.*FLANGE
      YDO = XLL(3,2) + 2.*X(1) + 2.*FLANGE
      ZDO = X(2)
      VDO = XDO * YDO * ZDO
      WRITE(*,*) '       '
      WRITE(*,*) 'ENTREE COMPARTMENT DIMENSION',(XLL(1,I),I=1,3)
      WRITE(*,*) 'STARCH COMPARTMENT DIMENSION',(XLL(2,I),I=1,3)
      WRITE(*,*) 'DESSERT COMPARTMENT DIMENSION',(XDO,YDO,ZDO)
      WRITE(*,*) 'DIMENSION OF INNER DESSERT TRAY',(XLL(3,I),I=1,3)
      WRITE(*,*) 'VOLUME OF (OUTER) DESSERT COMPARTMENT',VDO
  555 STOP
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(/' ','PROCEDURE HAS CONVERGED IN',I4,' ITERATIONS.'/
     *' THE SOLUTION IS AS FOLLOWS:')
 1001 FORMAT(' ',/,'PROCEDURE HAS NOT CONVERGED IN',I4,' ITERATIONS.'/
     *' ','THE CURRENT TRIAL SOLUTION AND SIMPLEX IS AS FOLLOWS:')
 1002 FORMAT(/' ','BASE SET OF VARIABLES VIOLATES SOME CONSTRAINT.')
 1003 FORMAT(/' ','ITERATION  0')
 1004 FORMAT(/' ','NOT MUCH IMPROVEMENT COULD BE ACHIEVED AFTER ',
     *,I4,'th ITERATION.')
 1005 FORMAT(//' ',5X,'AT TIME = min.',5X,'TEMP. = DEG. C.')
 1006 FORMAT(' ',5X,F15.3,5X,F15.3)
 3001 FORMAT(6X,7E15.5)
      END
```

```
C
C     Read input data for main optimization program
C ---------------------------------------------------------------
      SUBROUTINE OPTRD
C ---------------------------------------------------------------
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
C ..... READ BASIC DATA .....
      OPEN(5,FILE='OPT2.DAT',STATUS='OLD')
      READ(5,1000)NTITL,OLD
      READ(5,1001)NX,NY,NP,MAXIT,NFREQ
      DO 100 I=1,NX
  100 READ(5,1002)NAMEX(I),XL(I),XU(I),X(I)
      IF(NY)112,112,113
  113 DO 101 I=1,NY
  101 READ(5,1002)NAMEY(I),YL(I),YU(I)
  112 CONTINUE
      IF(NP)114,114,115
  115 DO 102 I=1,NP
  102 READ(5,1002)NAMEP(I),P(I)
  114 CONTINUE
      READ(5,1002)NAMEF,FR,FA
      CLOSE(5)
      RETURN
C ..... FORMAT STATEMENTS .....
 1000 FORMAT(A47,A2)
 1001 FORMAT(7I5)
 1002 FORMAT(A5,3F10.4)
      END
C
C     Print intermediate results and optimal design specifications
C -------------------------------------------------------------------
      SUBROUTINE OPTPR(IARG)
C -------------------------------------------------------------------
      DIMENSION NINT(50)
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      DATA NINT/1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,
     *22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,
     *43,44,45,46,47,48,49,50/
      GOTO (1,2,3,4,5,6),IARG
    1 CONTINUE
C ..... PRINT TITLE .....
      WRITE(6,2000)NTITL
      RETURN
    2 CONTINUE
C ..... PRINT TRIAL SOLUTION AND LIMITS .....
      WRITE(6,2002)
      WRITE(6,2003)
      DO 200 I=1,NX
  200 WRITE(*,2004)NAMEX(I),XL(I),XU(I),X(I)
      IF(NY)201,201,202
  202 WRITE(6,2005)
```

```
      WRITE(6,2003)
      DO 203 I=1,NY
  203 WRITE(6,2004)NAMEY(I),YL(I),YU(I),Y(I)
  201 CONTINUE
      IF(NP)204,204,205
  205 WRITE(6,2011)
      WRITE(6,2012)
      DO 206 I=1,NP
  206 WRITE(6,2004)NAMEP(I),P(I)
  204 CONTINUE
      WRITE(6,2010)
      WRITE(6,2006)
      WRITE(6,2004)NAMEF,F,FR,FA
      RETURN
    3 CONTINUE
C  ..... PRINT VALUES OF VARIABLES AT VERTICES OF CURRENT SIMPLEX ......
      KMAX1=KMAX+1
      WRITE(6,2007)KMAX1
C  ..... PRINTING DONE IN GROUPS OF SEVEN .....
      KK=1
      KKK=7
  400 CONTINUE
      KKKK=KKK
      IF(KKK.GE.KMAX1)KKK=KMAX1
      IF(KKK.EQ.KMAX1)KKKK=KKK-1
      WRITE(6,2008) (NINT(I),I=KK,KKK)
      DO 301 I=1,NX
      XX(I,KMAX1)=XC(I)
  301 WRITE(6,2004)NAMEX(I), (XX(I,K),K=KK,KKK)
      IF(NY)303,303,304
  304 DO 305 I=1,NY
  305 WRITE(6,2004)NAMEY(I), (YY(I,K),K=KK,KKKK)
  303 CONTINUE
      WRITE(6,2004)NAMEF, (FF(K),K=KK,KKKK)
      IF(KKK.EQ.KMAX1)GOTO 401
      KK=KK+7
      KKK=KKK+7
      GOTO 400
  401 CONTINUE
      RETURN
    4 CONTINUE
C  ..... PRINT RESULTS AT CURRENT ITERATION ......
      WRITE(*,*) '          '
      WRITE(6,2009)NIT,JG,FDEV,FMIN
      RETURN
    5 CONTINUE
      RETURN
    6 CONTINUE
      RETURN
C  ..... FORMAT STATEMENTS .....
 2000 FORMAT(' ',A47)
 2002 FORMAT(' ','INDEPENDENT VARIABLES')
 2003 FORMAT(' ',1X,'NAME',4X,'LOWER BOUND',4X,'UPPER BOUND',10X,
     *'VALUE'/)
 2004 FORMAT(' ',A5,1P7E15.5)
 2005 FORMAT(' ','DEPENDENT VARIABLES')
 2006 FORMAT(' ',1X,'NAME',10X,'VALUE',8X,'REL DEV',8X,'ABS DEV'/)
 2007 FORMAT(' ','VARIABLES IN SIMPLEX (CENTROID IS VERTEX',I3,')')
 2008 FORMAT(' ','VERTEX',I14,7I15)
 2009 FORMAT(' ','ITERATION',I4,' ENTERING VERTEX',I3,' FDEV =',1PE12.4,
     *' FMIN =',1PE12.4)
 2010 FORMAT(' ','OBJECTIVE FUNCTION')
 2011 FORMAT(' ','PARAMETERS')
```

```
 2012 FORMAT(' ',1X,'NAME',10X,'VALUE'/)
      END
C
C     Test for violation of implicit constraints in main program
C ----------------------------------------------------------------------
      SUBROUTINE IMTST(N,NMAX,IFLAG,IND)
C ----------------------------------------------------------------------
      CHARACTER NTITL*47,NAMEF*5,NAMEX(12)*5,NAMEY(30)*5,NAMEP(1)*5,
     *OLD*2
      COMMON/OPT/ F,X(12),Y(30),P(1)
      COMMON/STORE/ NX,NY,NP,XL(12),XU(12),YL(30),YU(30),
     *XC(12),XX(12,24),YY(30,24),FF(24),JG,NIT,
     *ALPHA,BETA,KMAX,MAXIT,FR,FA,FDEV,FMIN,NFREQ
      COMMON/ASTORE/ NTITL,NAMEF,NAMEX,NAMEY,NAMEP,OLD
      IFLAG=0
      N=1
C ..... EVALUATE OBJECTIVE FUNCTION AND DEPENDENT VARIABLES .....
  108 CALL MODEL(IND)
      IF(NY)300,300,301
  300 RETURN
  301 CONTINUE
C ..... TEST TO SEE IF ANY IMPLICIT CONSTRAINT HAS BEEN VIOLATED .....
      DO 103 I=1,NY
      IF(Y(I)-YL(I))101,102,102
  102 IF(YU(I)-Y(I))101,103,103
  103 CONTINUE
      RETURN
C ..... BECAUSE TRIAL POINT VIOLATES IMPLICIT CONSTRAINTS, MOVE TO
C       FRACTIONAL DISTANCE BETA FROM CENTROID OF OTHER POINTS .....
  101 DO 104 I=1,NX
  104 X(I)=XC(I)+BETA*(X(I)-XC(I))
      IF(N-NMAX)106,107,107
  106 N=N+1
      GOTO 108
C ..... TRIAL POINT DID NOT SATISFY IMPLICIT CONSTRAINT AFTER NMAX
C       MOVES TOWARD CENTROID OF OTHER POINTS .....
  107 IFLAG=1
      RETURN
      END
C
C     Print error messages for main program
C ---------------------------------------------------------------
      SUBROUTINE FAIL(NARG)
C ---------------------------------------------------------------
      WRITE(6,1000)NARG
      CALL OPTPR(2)
      CALL OPTPR(3)
      RETURN
 1000 FORMAT(' ','ERROR ENCOUNTERED IN OPTIMM'/' ','TYPE',I3,
     *' CONSTRAINT VIOLATED')
      END
C
C     Generate random numbers for optimization iterations
C
C ---------------------------------------------------------------
      SUBROUTINE GGUBS (DSEED,R)
C ---------------------------------------------------------------
      REAL R
      DOUBLE PRECISION   DSEED
C                                  SPECIFICATIONS FOR LOCAL VARIABLES
      INTEGER            I
      DOUBLE PRECISION   D2P31M,D2P31
C                                  D2P31M=(2**31) - 1
```

```
C                                    /   D2P31 =(2**31)(OR AN ADJUSTED VALUE)
      DATA                 D2P31M/2147483647.D0/
      DATA                 D2P31/2147483648.D0/
C                                        FIRST EXECUTABLE STATEMENT
         DSEED = DMOD(16807.D0*DSEED,D2P31M)
      R = DSEED / D2P31
      RETURN
      END
C
C     Estimate thermal processing lethality and time-temperature history
C     for each of the compartments in the tray
C -----------------------------------------------------------------------
      SUBROUTINE MODEL(IND)
C -----------------------------------------------------------------------
      CHARACTER*15 MEALS$(3)
      DIMENSION XL(3),X(3),TTHEAT(3),BI(3),FIMM(3)
      COMMON/OPT/ OBJ,XI(12),Y(30),PAR(1)
      COMMON/COND1/FLANGE,G,HEAD,V(3),XLL(3,3)
      COMMON/COND/ XKINS,TCOOL,TREF(3),XX(3,3),ZZ(3),FP(3)
     *,XK(3),ALPHA(3),HTA
      COMMON/FANDJ/C(3),CJ(3),FH(3),HJ(3),THEAT1,TI,TR,TC
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
C  ..... INPUT DATA ......
C  XI(1): INSULATION THICKNESS OF DESSERT TRAY
C  XI(2): HEIGHT OF THE WHOLE TRAY
C  XI(3): LENGTH OF THE ENTREE TRAY
C  G; G BETWEEN TRAYS
C  V(I): VOLUME OF EACH TRAY (INNER VOLUME)
C  XLL(I,J): DIMENSION OF ITH TRAY (INNER)
C
C     CONSTRAINTS FOR TRAY DESIGN
C     LENGTH: 10 INCHES (24 CM + 2 EDGES)
C     DEPTH:  1.1811 INCHES (3 CM)
C     INSULATION THICKNESS: 0.4 CM
C     GAP BETWEEN COMPARTMENTS: 0.8 CM
C
      IF(IND.EQ.1.OR.IND.EQ.3) GO TO 10
      GO TO 20
   10 OPEN(UNIT=7,FILE='TRAYDESI1.DAT',STATUS='OLD')
      READ(7,1) G
      READ(7,1) HTA,TCOOL,XKINS
      READ(7,1) TR,TI,TC
      DO 11 I=1,3
      READ(7,2) MEALS$(I)
      READ(7,1) V(I),XX(I,1),XX(I,2),XX(I,3)
      READ(7,3) XK(I),ALPHA(I)
   11 READ(7,1) ZZ(I),TREF(I),FP(I)
      CLOSE (UNIT=7)
      WRITE(6,5) (MEALS$(II),II=1,3)
C  ..... CALCULTE THE DIMESION OF THE TRAYS .....
      IF(TREF(3).EQ.100.0) THEN
      FLANGE = 0.006
      HEAD = 0.006
      ELSE
      FLANGE = 0.0
      HEAD = 0.0
      ENDIF
   20 DO 12 I=1,3
      XLL(I,3) = (XI(2) - HEAD)/2.
   12 CONTINUE
      XLL(3,3) = (XI(2) - HEAD - 2.*XI(1))/2.
      XLL(1,1) = XI(3)/2.
```

```
      XLL(1,2) = V(1)/(4.*XLL(1,1)*XLL(1,3)) / 2.
      CHECK = 0.3 * XLL(1,1)
      IF(XLL(1,2).GE.CHECK) THEN
      GOTO 14
      ELSE
      XLL(1,1) = SQRT(V(1)/(8.*0.3*XLL(1,3)))
      XLL(1,2) = 0.3 * XLL(1,1)
      ENDIF
   14 AREA2 = V(2) / (2.*XLL(2,3))
      AREA3 = V(3) / (2.*XLL(3,3))
      A = 4.*(XLL(1,1)-0.004-XI(1)-FLANGE)
      B = -4.*(FLANGE+XI(1))*(XLL(1,1)-0.004-XI(1)-FLANGE)-AREA2-AREA3
      C1 = (FLANGE + XI(1)) * AREA2
      XLL(2,2) = (-1.*B + SQRT(B*B - 4.*A*C1)) / (2.*A)
      XLL(2,1) = (V(2)/(4.*XLL(2,2)*XLL(2,3)))/2.
      XLL(3,2) = XLL(2,2) - XI(1) - FLANGE
      XLL(3,1) = XLL(1,1) - XLL(2,1) - 0.004 - XI(1) - FLANGE
      Y(1)=4.*XI(2)*(XLL(3,1)+XI(1)+FLANGE)*(XLL(3,2)+XI(1)+FLANGE)
      IF(XLL(2,2).LE.0.0.OR.XLL(3,3).LE.0.0) Y(1)=-1000.
      IF(Y(1).LT.0.0) RETURN
      Y(2) = XLL(2,2)*2.
      Y(3) = XLL(3,3)*2. + HEAD
C  ..... CALCULATE PROCESSING TIME FOR EACH MEAL  .....
      T0 = TI
      T1 = TR
      TW = TC
      DO 200 I = 1, 2
      TK=XK(I)
      AL=ALPHA(I)
      Z=ZZ(I)
      TRE=TREF(I)
      DO 100 J=1,3
      XL(J)=XLL(I,J)
      X(J)=XX(I,J)
C     WRITE(6,*) XL(J)
  100 CONTINUE
      HT = HTA
      CALL EIGEN(AL,XL,TK,HT,BI,FH(I),HJ(I))
      CJ(I) = 1.4
      C(I) = FH(I)
      CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,-1.,FP(I),THEAT1,FVALUE
      IF(THEAT1.GE.300.) GO TO 201
      TTHEAT(I)=THEAT1
      FIMM(I)=FVALUE
C     WRITE(6,*) HJ(I),FH(I),TTHEAT(I),FIMM(I)
  200 CONTINUE
      IF(TTHEAT(1).GT.TTHEAT(2)) THEN
      THEAT1=TTHEAT(1)
      FIMAX=FIMM(1)
      IMAX=1
      ELSE
      THEAT1=TTHEAT(2)
      FIMAX=FIMM(2)
      IMAX=2
      ENDIF
      Y(4) = THEAT1
  201 DO 206 I = 1,3
      IF(I.EQ.IMAX) GOTO 205
      TK=XK(I)
      AL=ALPHA(I)
      Z=ZZ(I)
      TRE=TREF(I)
      DO 204 J=1,3
```

```
      XL(J)=XLL(I,J)
      X(J)=XX(I,J)
  204 CONTINUE
      IF(I.NE.3) THEN
      HT = HTA
      ELSE
      HT=1./(1./HTA+XI(1)/XKINS)
      ENDIF
C
C     ESTIMATE THE STERILIZING VALUES FOR ALL THE FOODS BASED ON THE
C     PROCESSING TIME THEAT1 FOR THE FOOD WHICH IS LEAST OVER-PROCESSED.
C
      CALL EIGEN(AL,XL,TK,HT,BI,FB(I),HJ(I))
      CJ(I) = 1.4
      C(I) = FH(I)
      CALL PROCESS(T0,T1,TW,HJ(I),FH(I),CJ(I),C(I),Z,-1.,THEAT1,-1.,-1.,FVALUE
      Y(I+4) = FVALUE
      Y(8) = T(251)
      GO TO 206
  205 Y(I+4) = FIMAX
  206 CONTINUE
      OBJ=ABS(Y(5)-FP(1))+ABS(Y(6)-FP(2))+ABS(Y(7)-FP(3))
      RETURN
C  ..... FORMAT STATEMENTS .....
    1 FORMAT(4F10.5)
    2 FORMAT(A10)
    3 FORMAT(F10.4,E10.4)
    5 FORMAT(' MEAL NAMES ARE ',3(A7,2X))
      END
C  ----------------------------------------------------------------------
C     Calculate f and j values for each meal in the compartment tray
C  ----------------------------------------------------------------------
      SUBROUTINE EIGEN(AL,XL,TK,HT,BI,FHI,HJI)
C  ----------------------------------------------------------------------
      DIMENSION BI(3),XL(3),BETA1(3),FI(3),XJI(3)
      COMMON/THISTORY/ TRE
      FNF(X,BI1)=X*TAN(X)-BI1
      DO 1240 I=1,3
      BI(I)=HT*XL(I)/TK
      BETA1(I) = 0.0
      STP=3.141592654
      STP1=0.001
      STP2=3.141592654/2.-0.001
      XCRIT=0.00001
      FCRIT=0.0001
      IF(BI(I).EQ.0.0) THEN
      BETA1(I)=0.0
      GO TO 1225
      ELSE
      GO TO 1200
      ENDIF
 1200 X1=STP1
      X2=STP2
      ICOUNT = 1
 1210 F1=FNF(X1,BI(I))
      F2=FNF(X2,BI(I))
 1215 FMULT=F1*F2
      IF(FMULT.GT.0.0) GOTO 1225
C  ..... BISECTIONAL METHOD FOR ESTIMATION OF ROOTS .....
 1000 XERR=ABS(X1-X2)/2.0
      X3=(X1+X2)/2.
      F3=FNF(X3,BI(I))
      IF(I.GT.200) GOTO 1220
```

```
      IF(XERR.LT.XCRIT) GO TO 1220
      IF(ABS(F3).LT.FCRIT) GO TO 1220
      IF(F3*F1.LE.0.0) THEN
      X2=X3
      F2=F3
      ELSE
      X1=X3
      F1=F3
      ENDIF
      ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1)BI(I)
      GO TO 1210
 1220 BETA1(I) = X3
      GO TO 1230
 1225 ICOUNT = ICOUNT + 1
      IF(ICOUNT.GT.200) WRITE(6,1) BI(I)
      X1 = STP + STP1
      X2 = STP + STP2
      F1 = FNF(X1,BI(I))
      F2 = FNF(X2,BI(I))
      GO TO 1215
 1230 FI(I) = LOG(10.0) *XL(I)*XL(I) / (BETA1(I)*BETA1(I)*AL) / 60.
      XJI(I) = 2.0 * SIN(BETA1(I)) / (BETA1(I) +SIN(BETA1(I))*COS(BETA1(I)))
C     WRITE(6,*) BI(I), BETA1(I), XL(I), FI(I), XJI(I)
 1240 CONTINUE
      F = 0.0
      HJI = 1.0
      DO 1260 I1 = 1,3
      F = F + 1.0 / FI(I1)
      HJI = HJI * XJI(I1)
 1260 CONTINUE
      FHI = 1.0 / F
 1280 RETURN
    1 FORMAT(' DONT HAVE ROOT OF TRANSCENDENTAL EQUA.',F12.4)
      END
C
C     ESTIMATE PROPER HEAT PROCESSES OF RETORTABLE PLASTIC PACKAGE
C     FOR MULTIPLE FOODS. DEVELOPED MAINLY BASED ON THE PROGRAMS BY
C     DR. K. HAYAKAWA,
C     ADVANCES IN FOOD RESEARCH, VOL. XX. PP. 75-141, 1977.
C     THIS SUBROUTINE SOLVES 2 TYPES OF PROBLEMS. THEY INCLUDE:
C       TYPE B: GIVEN Fp, Solve for tb (thermal processing time)
C       TYPE A: GIVEN tb, Calculate the equivalent Fp
C
C ********************************** NOMENCLATURE **********************************
C     C    Slope index of cooling curve
C     CJ   Intercept coefficient of cooling curve
C     FH   Slope index of heating curve
C     HJ   Intercept coefficient of heating curve
C     FP1  Target sterilizing value
C     FPP  Estimated sterilizing value for given TG or TMG
C     T0   Initial temperature of food (Deg. C.)
C     T1   Holding temperature heating medium (Deg. C.)
C     TANS Length of heating phase to be estimated. A thermal process with TANS
C          minutes of processing time produces a target sterilizing value FP1
C     TG   Food temperature at end of heating phase of thermal process.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TG = - 1.0.
C     TMG  Length of heating phase.
C          When a problem is for estimating TANS or when an actual TG value
C          is given, Set TMG = -1.0
C     TW   Cooling medium temperature (Deg. C.)
C ***********************************************************************************
```

```
C
C  -----------------------------------------------------------------
      SUBROUTINE PROCESS(T0,T1,TW,HJ,FH,CJ,C,Z,TG,TMG,FP1,TANS,FPP)
C  -----------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      COMMON/TEMPT/ T(300),TM(300)
      ABC(1)=-1.0
      ABC(2)=-0.8302239
      ABC(3)=-0.4688488
      ABC(4)=0.0
      ABC(5)=0.4688488
      ABC(6)=0.8302239
      ABC(7)=1.0
      H(1)=0.0476190
      H(2)=0.2768260
      H(3)=0.4317454
      H(4)=0.4876190
      H(5)=0.4317454
      H(6)=0.2768260
      H(7)=0.0476190
      DO 141 J=1,300
      T(J)=0.
  141 TM(J)=0.
      FPP=0.
      YFP = 0.
      YFP1 = 0.
      YFP2 = 0.
      TANS=0.
      IF(FP1.LE.0.) GO TO 146
C
C     This is a Type B Problem.
C     It solves for the processing time TANS to achieve target Fp.
C
      TMG1 = FP1
      FPP = 0.
      TMG2 = 40. * FP1
  142 TMG = TMG1
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
C     WRITE(6,*)hj,fh,t0,t1,TMG,DEL,TM(251),T(251)
      CALL SIMP(T,DEL,251,Z,FPH1)
C     WRITE(6,*)T(251),del,z,FPH1
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
C     WRITE(6,*)FPC
      FPP1 = FPH1 + FPC
      YFP1 = FP1 - FPP1
  143 TMG = TMG2
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH2)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP2 = FPH2 + FPC
      YFP2 = FP1 - FPP2
      TMG = (TMG1+TMG2) / 2.0
      CALL HEAT(HJ,FH,T0,T1,-1.0,TMG,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP = FPH + FPC
      YFP = FP1 - FPP
C     write(6,*) tmg, fpp
      IF((YFP1*YFP).GT.0..AND.(YFP2*YFP).GT.0.) GOTO 148
      IF(ABS(FPP-FP1).LE.0.1) GO TO 144
      YCHECK = YFP1 * YFP
```

```
      IF(YCHECK.LE.0.0) THEN
      TMG2 = TMG
      GO TO 143
      ELSE
      TMG1 = TMG
      GO TO 142
      ENDIF
  144 TANS = TMG
      GO TO 150
C
C     This is a type A problem.
C     Given heating time, solve for actual Fp.
C
  146 TG = T1 - HJ *(T1-T0) *10.**(-TMG /FH)
      CALL HEAT(HJ,FH,T0,T1,TG,-1.0,251,DEL,TM,T)
      CALL SIMP(T,DEL,251,Z,FPH)
      CALL FCOL(FPC,CJ,C,T(251),TW,Z)
      FPP = FPH + FPC
      GO TO 150
  148 WRITE(6,149)
  149 FORMAT('     ','PROCESSING TIME IS LARGER THAN 40 Fp.',/,
     *'     ','Please modify the program!')
  150 RETURN
      END
C
C     Calcualte food temperatures on a heating curve
C     The equations were updated (from the 1977 Reference)
C     with reference to Lekwauwa, A. N. and Hayakawa, K., 1986.
C     J. Food Sci. 51(4): 1042-1049, 1056.
C
C ****************************** NOMENCLATURE ***************************
C     DEL  Time increment for heating phase
C     NTRM Number of food temperatures to be estimated. 2 < NTRM <= 300
C     T    Food temperature estimated (Deg. C.)
C     TM   Heating times at which food temperatures reach to T's
C ***********************************************************************
C ---------------------------------------------------------------------
      SUBROUTINE HEAT(HJ,FH,T0,T1,TG,TMG,NTRM,DEL,TM,T)
C ---------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION T(300),TM(300)
      AN(A,AF,AJ) = (A/AF - ALOG10(AJ)) / (A/AF)
      BA(AJ,A,AF,BN) = A* (A/AF - ALOG10(AJ))**(BN)
      TA(TMA,BAA,AAN)=T1-(T1-T0)*EXP(-2.30259*EXP(ALOG(
     *TMA/BAA)*(1./AAN)))
      TIA(BAA,TP,AAN)=BAA*((ALOG10((T1-T0)/(T1-TP)))**AAN)
      BB(TLB)=(1./TLB)*(ATAN((ALOG10(T1-T0))/(ALOG10(HJ*
     *(T1-T0))-TLB/FH))-0.785398)
      TB(BBB,TMB)=T1-(T1-T0)**(1./TAN(BBB*TMB+0.785398))
      TIB(BBB,TP)=(1./BBB)*(ATAN((ALOG10(T1-T0))/(ALOG10(T1
     *-TP)))-0.785398)
      BC(TLC)=(1./TLC)*ACOS((ALOG10(HJ*(T1-T0))-TLC/FH
     *)/(ALOG10(T1-T0)))
      TC(BCC,TMC)=T1-(T1-T0)**(COS(BCC*TMC))
      TIC(BCC,TP)=(1./BCC)*ACOS((ALOG10(T1-TP))/(ALOG10(T1
     *-T0)))
      TD(TMD)=T1-HJ*(T1-T0)*EXP(-2.30259*(TMD/FH))
      TID(TP)=FH*ALOG10(HJ*(T1-T0)/(T1-TP))
      DO 90 I=1,300
      T(I)=0.0
   90 TM(I)=0.0
      NXX=NTRM-1
      IF(HJ.LT.0.001)GO TO 1
```

```
      IF(HJ.LT.0.40)GO TO 2
      IF(HJ.LE.0.999999)GO TO 3
      IF(HJ.LE.1.00001)GO TO 7
      IF(HJ.GT.6500.0)GO TO 4
      GO TO 6
    1 WRITE(*,5)
    5 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH < 0.001')
    2 TL = FH * (0.3913 - 0.3737 * ALOG10(HJ))
      RN = AN(TL,FH,HJ)
      B = BA(HJ,TL,FH,RN)
      IF(TG.LT.0.0)GO TO 8
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 9
      TMH=TID(TG)
      TH=TG
      GO TO 10
    9 TMH=TIA(B,TG,RN)
      TH=TG
      GO TO 10
    8 IF(TMG.LT.TL)GO TO 11
      TH=TD(TMG)
      TMH=TMG
      GO TO 10
   11 TH=TA(TMG,B,RN)
      TMH=TMG
   10 T(1)=T0
      TM(1)=0.
      DEL=TMH/NXX
      T(NTRM)=TH
      TM(NTRM)=TMH
      DO 100 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 102
      T(I)=TA(TMI,B,RN)
      GO TO 100
  102 T(I)=TD(TMI)
  100 CONTINUE
      GO TO 60
    3 TL = 0.9*FH*(1.-HJ)
      B = BB(TL)
      IF(TG.LT.0.0)GO TO 19
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 20
      TMH=TID(TG)
      TH=TG
      GO TO 21
   20 TMH=TIB(B,TG)
      TH=TG
      GO TO 21
   19 IF(TMG.LT.TL)GO TO 22
      TH=TD(TMG)
      TMH=TMG
      GO TO 21
   22 TH=TB(B,TMG)
      TMH=TMG
   21 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 30 I=2,NXX
```

```
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 32
      T(I)=TB(B,TMI)
      GO TO 30
   32 T(I)=TD(TMI)
   30 CONTINUE
      GO TO 60
    7 IF(TG.LT.0.0)GO TO 34
      TMH=TID(TG)
      TH=TG
      GO TO 35
   34 TH=TD(TMG)
      TMH=TMG
   35 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 40 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      T(I)=TD(TMI)
   40 CONTINUE
      GO TO 60
    4 WRITE(*,43)
   43 FORMAT(1X,'TM & T ESTIMATED BY SUBROUTINE HEAT ARE QUESTIONABLE
     *SINCE JH > 6500.0')
    6 IF(HJ.LE.5.8) TL = 0.7*FH*(HJ-1.)
      IF(HJ.GT.5.8) TL = 1.54 *FH *ALOG10(HJ/1.8)
      B = BC(TL)
      IF(TG.LT.0.0)GO TO 44
      TEMPL=TD(TL)
      IF(TG.LE.TEMPL)GO TO 45
      TMH=TID(TG)
      TH=TG
      GO TO 46
   45 TMH=TIC(B,TG)
      TH=TG
      GO TO 46
   44 IF(TMG.LT.TL)GO TO 47
      TH=TD(TMG)
      TMH=TMG
      GO TO 46
   47 TH=TC(B,TMG)
      TMH=TMG
   46 T(1)=T0
      TM(1)=0.
      T(NTRM)=TH
      TM(NTRM)=TMH
      DEL=TMH/NXX
      DO 55 I=2,NXX
      TMI=DEL*(I-1)
      TM(I)=TMI
      IF(TMI.GE.TL)GO TO 57
      T(I)=TC(B,TMI)
      GO TO 55
   57 T(I)=TD(TMI)
   55 CONTINUE
   60 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM TWO FOOD TEMPERATURES
```

```
C     DEL MINUTE APART from each other DURING THE HEATING PHASE
C
C ******************************  NOMENCLATURE ********************************
C     DELF Estimated sterilizing value (min.)
C     TH Food temperature (TH > TL)
C     TL Food temperature (TL < TH)
C     Z  Slope index of thermal death time curve (C. Deg.)
C ****************************************************************************
C  ---------------------------------------------------------------
      SUBROUTINE FDIF(DELF,T1,TH,TL,DEL,Z)
C  ---------------------------------------------------------------
      TM=FTG(T1,TH,TL,0.5*DEL,0.,DEL)
      DELF=DEL/6.0*(RT(TL,Z)+4.*RT(TM,Z)+RT(TH,Z))
      RETURN
      END
C  ---------------------------------------------------------------
      FUNCTION RT(T,Z)
C  ---------------------------------------------------------------
      COMMON/THISTORY/ TRE
      IF(ABS(T-TRE).LT.1.E-5)GO TO 1
      TRAT=(T-TRE)/Z
      IF(TRAT.LT.-6.0)GO TO 3
      RT=10.**TRAT
      GO TO 2
    3 RT=1.0E-6
      GO TO 2
    1 RT=1.0
    2 RETURN
      END
C  ---------------------------------------------------------------
      FUNCTION FX(FA,FB,TA,TB,TX)
C  ---------------------------------------------------------------
      FX=FA+(TX-TA)*(FB-FA)/(TB-TA)
      RETURN
      END
C  ---------------------------------------------------------------
      FUNCTION FTG(T1,TH,TL,TMG,TML,DEL)
C  ---------------------------------------------------------------
      IF(ABS(TMG-TML).LE.1.E-5)GO TO 1
      IF(ABS(T1-TH).LE.1.E-5)GO TO 2
      R=(T1-TH)/(T1-TL)
      IF(R.GE.0.9999)GO TO 2
      FTG=T1-(T1-TL)*R**((TMG-TML)/DEL)
      GO TO 3
    1 FTG=TL
      GO TO 3
    2 FTG=(TH+TL)/2.
    3 RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM A COOLING CURVE
C
C ******************************  NOMENCLATURE ****************************
C     FPC Estimated sterilizing value (min.) during cooling phase
C *************************************************************************
C  ---------------------------------------------------------------------
      SUBROUTINE FCOL(FPC,CJ,C,TG,TW,Z)
C  ---------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      COMMON/COMA/ABC(7)
      COMMON/COMH/H(7)
      DIMENSION TMC(7),TC(7)
      DO 1 I=1,7
```

```
      TMC(I)=0.
    1 TC(I)=0.
      IF(ABS(CJ-1.0).LT.1.0E-4)GO TO 2
      CALL COOL(CJ,C,TL,TG,TW,TMC,TC)
      CALL RATE(FPA,TC,Z,0.,TL)
      GO TO 3
    2 FPA=0.
      TL=0.
    3 CALL COOLA(CJ,C,TL,TG,TW,TMC,TC,Z)
      CALL RATE(FPB,TC,Z,TL,TMC(7))
      FPC=FPA+FPB
      RETURN
      END
C
C     ESTIMATE A STERILIZING VALUE FROM DATA ON FOOD
C     TEMPERATURE COLLECTED AT UNIFORM TIME INTERVALS
C
C ****************************** NOMENCLATURE ***************************
C     DELX uniform time interval (min.)
C     NO   Number of temperature data collected
C     Y    Vector of temperature data (Deg. C.)
C ***********************************************************************
C ---------------------------------------------------------------------
      SUBROUTINE SIMP(Y,DELX,NO,Z,FP)
C ---------------------------------------------------------------------
      COMMON/THISTORY/ TRE
      DIMENSION Y(300)
      NN=NO/2
      NM=NN*2
      IF(NM.EQ.NO)GO TO 10
      NM=NO
      GO TO 11
   10 NM=NO-1
   11 IF(NO-3)1,2,3
    1 IF(NO.EQ.2)GO TO 12
      IF(NO.EQ.1)GO TO 13
      WRITE(*,14)
   14 FORMAT(' ','NO FP IS ESTIMATED SINCE NO < 1 AT SUBROUTINE SIMP')
   13 FP=0.
      GO TO 6
    2 FP=DELX/3.*(RT(Y(1),Z)+4.*RT(Y(2),Z)+RT(Y(3),Z))
      GO TO 6
    3 FP=RT(Y(1),Z)+RT(Y(NM),Z)
      M=NM-1
      FPA=0.
      DO 4 I=2,M,2
    4 FPA=FPA+RT(Y(I),Z)
      IF(NO.EQ.4)GO TO 15
      FPB=0.
      M=NM-2
      DO 5 I=3,M,2
    5 FPB=FPB+RT(Y(I),Z)
      GO TO 16
   15 FP=DELX/3.*(FP+4.*FPA)
      GO TO 20
   16 FP=DELX/3.*(FP+4.*FPA+2.*FPB)
      IF(NM.EQ.NO)GO TO 6
   20 FP=FP+DELX/2.*(RT(Y(NO-1),Z)+RT(Y(NO),Z))
      GO TO 6
   12 FP=DELX/2.*(RT(Y(1),Z)+RT(Y(2),Z))
    6 RETURN
      END
C
```

```
C     CALCULATE 7 TEMPERATURES ON A CURVILINEAR PORTION OF
C     A COOLING CURVE. THESE TEMPERATURES ARE THEN USED TO
C     CALCULATE A STERILIZING VALUE BY USING THE 7 POINT
C     LOBBATO QUADRATURE FORMULA.
C
C ********************************* NOMENCLATURE *************************
C     FC    Slope index of cooling curve
C ***********************************************************************
C ---------------------------------------------------------------
      SUBROUTINE COOL(CJ,FC,TL,TG,TW,TM,T)
C ---------------------------------------------------------------
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      DIMENSION TM(7),T(7)
      TXA(Y,BY,YN)=TW+(TG-TW)*EXP(-2.302585*EXP(ALOG(Y/BY)*(1./YN)))
      TXB(Y,BY)=TW+(TG-TW)**(1./TAN(BY*Y+0.785398))
      TXC(Y,BY)=TW+(TG-TW)**(COS(BY*Y))
      TMX(X,TK)=TK/2.+TK*X/2.
      DO 50 I=1,7
      TM(I)=0.
   50 T(I)=0.
      IF(CJ.GE.0.001)GO TO 11
   10 WRITE(*,12)
   12 FORMAT(1X,'TM & T VLAUES ESTIMATED BY SUBROUTINE COOL ARE QUESTI
     *ONABLE SINCE CJ < 0.001')
      GO TO 13
   11 IF(CJ.LE.0.4)GO TO 13
      IF(CJ.LE.0.999999)GO TO 14
      IF(CJ.LE.1.00001)GO TO 15
      IF(CJ.LE.6500.0)GO TO 16
      WRITE(*,17)
   17 FORMAT(1X,'TM & T VALUES ESTIMATED BY COOL ARE QUESTION
     *ABLE SINCE CJ > 6500.0')
      GO TO 16
   13 TL = FC * (0.3913 - 0.3737 * ALOG10(CJ))
      EN = (TL/CJ - ALOG10(CJ)) / (TL/CJ)
      B = TL * (TL/CJ - ALOG10(CJ))**(EN)
      T(1)=TG
      TM(1)=0.
      DO 18 I=2,7
      IF(I.EQ.4)GO TO 19
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   20 TXT=TXA(TM(I),B,EN)
      T(I)=TXT
      GO TO 18
   19 TM(I)=TL/2.
      GO TO 20
   18 CONTINUE
      GO TO 8
   15 WRITE(*,21)
   21 FORMAT(1X,'CALLING EXIT FROM COOL SINCE CJ=1.0')
      GO TO 8
   14 TL=0.9*FC*(1.-CJ)
      B=(1./TL)*(ATAN(ALOG10(TG-TW)/(ALOG10(CJ*(TG-TW))-TL/FC))-
     *0.7853982)
      TM(1)=0.
      T(1)=TG
      DO 22 I=2,7
      IF(I.EQ.4)GO TO 23
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   24 TXT=TXB(TM(I),B)
```

```
      T(I)=TXT
      GO TO 22
   23 TM(I)=TL/2.
      GO TO 24
   22 CONTINUE
      GO TO 8
   16 IF(CJ.LE.5.8) TL=0.7*FC*(CJ-1.)
      IF(CJ.GT.5.8) TL = 1.54 *FC *ALOG10(CJ/1.8)
      B=(1.0/TL)*ACOS((ALOG10(CJ*(TG-TW))-TL/FC)/ALOG10(TG-TW))
      TM(1)=0.
      T(1)=TG
      DO 25 I=2,7
      IF(I.EQ.4)GO TO 26
      TMZ=TMX(ABC(I),TL)
      TM(I)=TMZ
   27 TXT=TXC(TM(I),B)
      T(I)=TXT
      GO TO 25
   26 TM(I)=TL/2.
      GO TO 27
   25 CONTINUE
    8 RETURN
      END
C
C     CALCULATE 7 TEMPERATURES ON A LINEAR PORTION
C     OF A COOLING CURVE
C ----------------------------------------------------------------
      SUBROUTINE COOLA(CJ,FC,TL,TG,TW,TM,T,Z)
C ----------------------------------------------------------------
      DIMENSION TM(7),T(7)
      COMMON/COMA/ABC(7)
      COMMON/THISTORY/ TRE
      TX(Y)=TW+CJ*(TG-TW)*EXP(-2.302585*Y/FC)
      TMX(X,TBX,TIN)=(TBX+TIN)/2.+(TBX-TIN)*X/2.
      TMY(X,TBX)=TBX/2.+TBX*X/2.
      TIM(X)=FC*ALOG10(CJ*(TG-TW)/(X-TW))
      DO 50 I=1,7
      TM(I)=0.0
   50 T(I)=0.0
      IF(CJ.LE.0.999999)GO TO 8
      IF(CJ.LE.1.00001)GO TO 9
      GO TO 8
    9 TBL=TG
C .....WHEN CJ=1.0,THE COMPUTATIONAL FLOW IS BLANCHED TO 9. IN
C       THIS CASE TBL=TG SINCE THERE IS NO CURVELINEAR PORTION.....
      GO TO 10
    8 TBL=TX(TL)
   10 IF(TRE.NE.(5.*Z))GO TO 20
      TLOW=1.E-6
      GO TO 21
   20 TLOW=TRE - 5.*Z
   21 IF(TLOW.GE.TG)GO TO 1
      IF(TLOW.GE.TBL)GO TO 1
      IF(TLOW.GT.TW)GO TO 2
      IF(TLOW.LE.TW)GO TO 3
    1 TEND=TIM((TBL+TW)/2.)
    7 CONTINUE
      T(1)=TBL
      TM(1)=TL
      DO 4 I=2,7
      IF(I.EQ.4)GO TO 5
      IF(CJ.LE.0.999999)GO TO 11
      IF(CJ.LE.1.00001)GO TO 12
```

```
   11 TMT=TMX(ABC(I),TEND,TL)
    6 TM(I)=TMT
      GO TO 13
   12 TMT=TMY(ABC(I),TEND)
      GO TO 6
   13 T(I)=TX(TMT)
      GO TO 4
    5 IF(CJ.LE.0.999999)GO TO 14
      IF(CJ.LE.1.00001)GO TO 15
   14 TMT=(TEND+TL)/2.
      GO TO 6
   15 TMT=TEND/2.
      GO TO 6
    4 CONTINUE
      GO TO 16
    2 TEND=TIM(TLOW)
      GO TO 7
    3 TEND=TIM(TW+0.01*(TBL-TW))
      GO TO 7
   16 RETURN
      END
C
C     CALCULATE STERILIZING VALUES BY
C     APPLYING LOBBATO 7 POINT QUADRATURE FORMULA
C
C ******************************  NOMENCLATURE ***************************
C     R     Sterilizing value calculated (min.)
C     T     Seven temperatures (Deg. C.) used to calculate R value.
C     TBGIN Lower time limit of integration (min.)
C     TEND  Upper time limit of integration (min.)
C ************************************************************************
C  ----------------------------------------------------------
      SUBROUTINE RATE(R,T,Z,TBGIN,TEND)
C  ----------------------------------------------------------
      COMMON/COMH/H(7)
      COMMON/THISTORY/ TRE
      DIMENSION T(7)
      IF(T(1).NE.TRE)GO TO 2
      RA=H(1)
      GO TO 4
    2 RA=H(1)*10.**((T(1)-TRE)/Z)
    4 CONTINUE
      DO 1 I=2,7
      IF(T(I).NE.TRE)GO TO 5
      RA=RA+H(I)
      GO TO 1
    5 RA=RA+H(I)*10.**((T(I)-TRE)/Z)
    1 CONTINUE
      IF(TBGIN.GE.1.0E-3)GO TO 6
      R=TEND/2.*RA
      GO TO 7
    6 R=(TEND-TBGIN)/2.*RA
    7 RETURN
      END
```

APPENDIX I

TECHNICAL REPORT
ON
GAP EFFECTS ON HEAT PENETRATION
PARAMETERS OF MULTI-COMPARTMENT TRAY

GAP EFFECTS ON HEAT PENETRATION PARAMETERS OF MULTI-COMPARTMENT TRAY

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ABSTRACT

Investigations for the slowest-heating point and apparent heat transfer coefficients (h) for semi-rigid plastic multi-compartment trays were conducted. The temperature profile and slowest-heating point of the compartment were described in the paper. As far as lethality values are concerned, the geometric center could still be used as the slowest-heating point for thermal processing. The apparent heat transfer coefficients for both single trays and multi-compartment trays were determined by an optimization method based on three dimensions. The gap effects were discussed and gaps for pratical design were suggested. The investigations may have been fundamental to optimizing design of multi-compartment trays.

INTRODUCTION

Retortable plastic trays have gained popularity in recent years because of their light weight, reasonably long non-refrigerated shelf-life (1 to 2 years), microwaveability and design flexibility (Rice,1988). Most of the commercial retortable plastic food packages are single compartment trays. However, there is increasely interest in multi-compartment trays. One multi-compartment tray usually has three compartments. So that users could have three different items for one meal. Besides the multi-compartment tray may have potential advantiges of reducing material and energy consumption compared to single trays. To optimize the design of the tray, it is necessary to study thermal properties of multi-compartment.

The effectiveness of the thermal sterilization process may be measured by the F_o value at the slowest-heating point inside the food. Berry and Bush (1988) found that the location of the slowest-heating point changed with different orientations of metal lids of plastic containers, in which conduction-heating food was packaged.The lowest temperature in the food was located by moving thermocouples in vertical axis of the can. Since accurate predictions are not available for its location, a group or movement of thermocouples is usually applied to measure temperatures at different possible positions.

Peterson and Adams (1983) used empirical correlations for heat transfer in infinite slab geometry based on the slope of heating curve (Ball and Olson,1957) to determine apparent heat transfer coefficient. In 1989 a computer-based optimization method was developed by Lebowitz and Bhowmik to determine retortable pouch apparent heat transfer coefficients. The assumption of infinite slab for thin pillow-like pouches made h converge in one bisctional subroutine.

Many factors influencing the apparent heat transfer coefficients have been studied. Peterson and Adams (1983) studied flow rates effects on the apparent heat transfer coefficient of retortable pouches of institutional size. Weintraub et al.(1989) has found that small amount of entrapped air (<5ml) inside a package can lower h when processed at low air overpressure (<40kPa). However the gap effect has not been studied.

Apparent heat transfer coefficient may be defined as the following equation (R.L.Earle):

$$\frac{1}{h}=\frac{1}{h_{s1}}+\frac{x}{K}+\frac{1}{h_{s2}}$$

where h=apparent (or overall) heat transfer coefficient, h_{s1},h_{s2}=surface heat transfer coefficient for outside and inside of tray separately, x=thickness of tray material, K=thermal conductivity of tray material.

Brick-like single tray has six sides of heat transfer from outside to inside and driving force from each symmetric side is also symmetric. But for a compartment with a gap in one or two sides h_{s1} would be different, because gaps make convection different of heating medium. Therefore h and driving force of heat transfer would be different and nonsymmetric, and the slowest-heating point may shift away from the geometric center.

The objectives of this investigation were to examine the influencing extent of gaps between compartments on apparent heat transfer coefficients and location of the slowest-heating point for the multi-compartment tray.

MATERIAL AND METHOD

Multi-compartment tray and thermocouple location

Multi-compartment trays were made by thermoforming multilayered sheets containing polypropylene and ethylene vinyl alcohol (PP-EVOH-PP). Single trays were cut from multi-compartment trays with sealing edges. The trays were sealed with lidstock(aluminum-plastics). The test tray was one of four various trays which were designed to meet the lethal requirements of different food. The dimension of test compartments were 190x64x36 mm and 90x94x36 mm (test of h only). The multi-compartment tray had an original gap of 10 mm. The gap of 5 and 2.5 mm was reduced by sticking several pieses of the multilayers with silicone. For the comparison of h, single trays and compartment trays were cooked simultaneously. Duplicated experiments were conducted to obtain each data point.

A10 % of bentonite solution with thermal conductivity k 0.637 w/m.c, density 1.07 g/ml and heat capacity 3604 J/KgK (Niekamp et al.,1984) was used as a conduction-heating food simulation model and was packaged to the thickness of 34 mm.

Thermocouples(C-4,C-5.1,O.F.ECKLUND) were located at half thickness 5mm apart (10mm last) from the center of Compartment 1 by supports on the line as shown in Fig.1. This was for location of the slowest-heating point. For comparison of h between single trays and compartments, the thermocouples were in the geometric centers. Holes were punched in the trays to allow for insertion of the thermocouples.

Apparatus and materials

STOCK retort (pilot rotor 900) was used,which had a storage tank and a heating tank with temperature and air pressure control. For improved convection the water in the heating tank was circulated by a circulation pump (Fig.2). A data acquisition system was installed with a computer(IBM) to automatically record time-temperature history.

Trays were put between the plastic rackes of thickness of 12mm with grids of 33x33mm (20x20mm hole).

Thermal processing conditions

The steam-water heating medium of 10-15°C above 121°C was stored in the storage tank at a pressure of 200 kP_a . Heating was being started by opening the connection valve between the two tanks. During heating, the circulation pump,pressure and temperature controllers were on. It took 10-12 min for come-up time, 40-55 min for heating (121°C) and 25-40 min for cooling(dependent on dimensions of the tray and the desired F_o values). Intervals of 0.5 min were set for time-temperature history recording.

Optimization method

Once the slowest-heating point during the heating cycle was found, it was possible to determine h by an optimization method. Lebowitz and Bhowmik (1989) optimized h for pouches using the analytical equation developed by Ball and Olson(1957):

$$h=k\sqrt{2.303/(\alpha f_h)}\tan\sqrt{2.303a^2/(\alpha f_h)} \qquad (2)$$

where h=apparent heat transfer coefficient, k=thermal conductivity, α =thermal diffusivity, f_h=slope index of heating curve and a=half thickness of the slab. For the thickness of less than 1/8 -1/10 of the width, it is reasonable to optimize h with one dimension. But for trays like bricks, three dimensions should be considered. Take Pflug's suggestion(1965):

$$\frac{1}{f_h}=\frac{1}{f_l}+\frac{1}{f_w}+\frac{1}{f_d} \qquad (3)$$

f_j(j=l,w,d) may be obtained by the following equations(Ball and Olson):

$$N_{Bij}=\frac{ha_j}{k}=\beta_{1j}\tan\beta_{1j} \qquad (4)$$

$$f_j = \frac{2.303 a_j^2}{\beta_{1j}^2 \alpha} \tag{5}$$

where f_l, f_w and f_d = slope index of infinite slabs for lenth,width and depth of trays respectively, N_{Bi} = number of Biot, β_1 = Nth root of the boundary equation for the slab. The computer program consisted of two bisectional subroutines for β_1 and h. Boundaries for searching range were set small and big enough to cover the solution. Fig.3 showes the flow chart of optimization prgram.

RESULTS AND DISCUSSION

The slowest-heating point and Fo value

During the thermal process the slowest-heating point held the lowest F_o value. For single containers with uniform heating mediums geometric centers were the slowest-heating point. But for compartments with gaps in between, the slowest-heating point moved 4--5 mm away from the geometric center to gap sides. Fig.4 showed temperature-location profile at different time in the heating cycle. The longer the food had been cooked, the less the temperature differences would be. If the food was overcooked for a certain time, the temperature at all locations would reach retort temperature,and the profile would be a level line. The possible error of measured lowest temperature at 5 mm distance from the geometric center was -0.3%, since the temperature profile may be reasonably assumed symmetric and partially linear while the lowest temperature was above 90°C.

Theoratically thermal death time F is integrated from lethal rate curve against time. We calculated F_o value approximately by the following equation with LOTUS program:

$$F_o = t \sum \frac{1}{10^{(121-T_i)/z}} \tag{6}$$

where F_o = thermal death time at 121°C for organisms with z=10°C (min), z = °C temperature change required to change the TDT by a factor of 10 (°C), t = time interval for temperature record (0.5 min), T_i = recorded temperatures with 0.5 min interval (°C).Table 1 showes with increasing of gap size, influence of gap decreased, though the biggest difference was only 5%. Therefore the geometric centers could still serve as the slowest-heating points for the purpose of simulating thermal process.

Optimized apparent heat transfer coefficient

Both single trays and compartments had typical heating penetration curves. The curves for geometric center versus the slowest-heating point for compartment 1 were shown on Fig.5 and compartments versus single trays were shown on Fig.6. The data of experiments were so good and reproducable that made standard error < 0.0003 for regression of f_h.

Computer program ran without printing "fail". β_{1j} converged on $|\beta_{1j} \tan\beta_{1j} - N_{Bi}| \leq 0.0001$ or $\frac{|\beta_{11} - \beta_{12}|}{2} \leq 0.00001$. The optimization ends when $|f-f_h| < 0.01$ or $\frac{|h1-h2|}{2} \leq 0.001$ or a maximum of 50 iteration has been reached. The mean of optiimized apparent heat transfer coefficient was 133 W/m^2K with standard deviation of 21 W/m^2K for compartment trays and 200 W/m^2K with standard deviation of 73 W/m^2K for single trays .

Less convection on gap sides

Gaps affected both location of the slowest-heating point and apparent heat transfer coefficients of compartment trays. McCabe and Smith (1976) established empirical correlation for understanding of factors affecting h in turbulent flow heat exchange process for the analogous tubular case by dimensionless proup analysis. For the lack of better equations for rectangular case, the correlation pertaining to mass velocity may be used to explain gap effects:

$$h \ \alpha \ G^{0.8} \tag{7}$$

where h=appaerent heat transfer coefficient and G= mass velocity. Peterson and Adams (1983) presented data of apparent heat transfer coefficient for institute-size retortable plastic pouches with changing of mass velocity. As the velocity of heating medium increased 10 times, h increased only about a half. That meant for the rectangular case Formula 7 should be modefied with a smaller power.

In the gap of compartments convection was greatly reduced and less heat was transfered through the gap sides. This is the same as mass velocity is decreased in gap sides. Factors of affecting h may be gap sizes, area and distance to geometric center. However the test tray was chosen among four available sizes of multi-compartment trays considering all above factors to the most effective. Gap sizes seemed not influencing the

location of the slowest point and apparent heat transfer coefficients too much. If gap=0,two compartments become one single tray and the slowest-heating point should be the geometric center. It was sure that between 2.5 mm to 0 there would be a critical gap size below which the slowest-heating point and h would greatly influenced. Anyway the gap of 2.5 mm was small enough for the investigation because the sealing and thermoforming of multi-compartment trays needed bigger gaps.

CONCLUSIONS

The gap affects F_o value and h for multi-compartment trays. F_o was found changing from 5% to 0.9% with varies of gap from 2.5 to 10 mm respectively. The apparent heat transfer coefficient seemed almost no changes with difference of gap sizes.To determine h or measure F_o value for thermal processing of the multi-compartment tray, geometric centers may be used as the slowest-heating point. The devoloped optimization method may be feasible to estimate h of retortable plastic trays and other brick-like food package. A gap of at least 5--10 mm between compartments was suggested to make effective sealing and assure small gap effects.

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Table.1 F_o DIFFERENCES BETWEEN GEOMETRIC CENTER AND SLOWEST-HEATING POINT OF COMPARTMENT 1

Food dimension (mm)	Gap (area) (mm)	Slowest-heating point	F_o Difference*
190x64x34	2.5(190x34)	4--5mm away	5.0%
	5(190x34)		3.0%
	10(190x34)		0.9%

* F_o = 3 -- 10 min

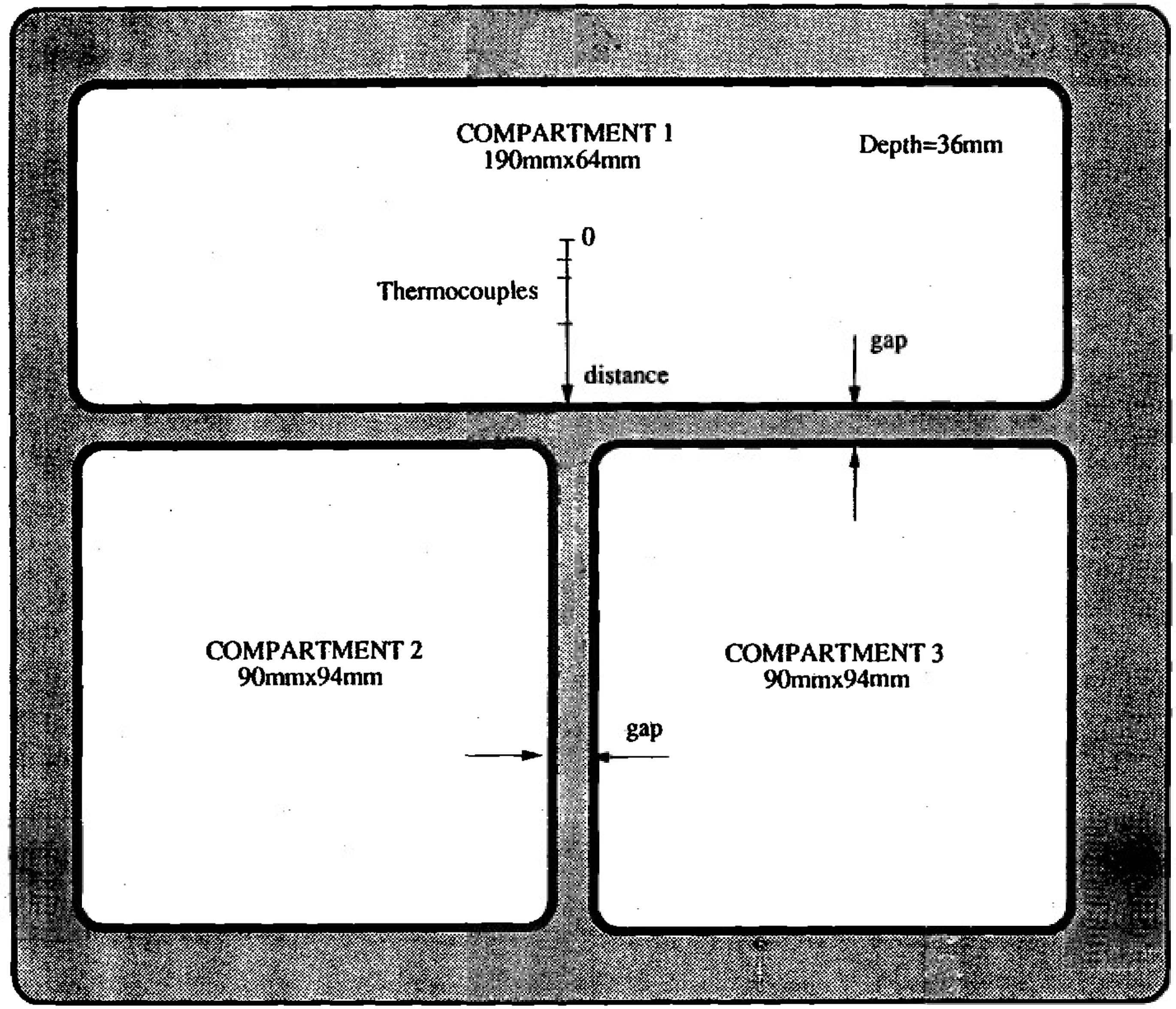

FIG. 1 MULTI-COMPARTMENT TRAY AND THERMOCOUPLE LOCATION

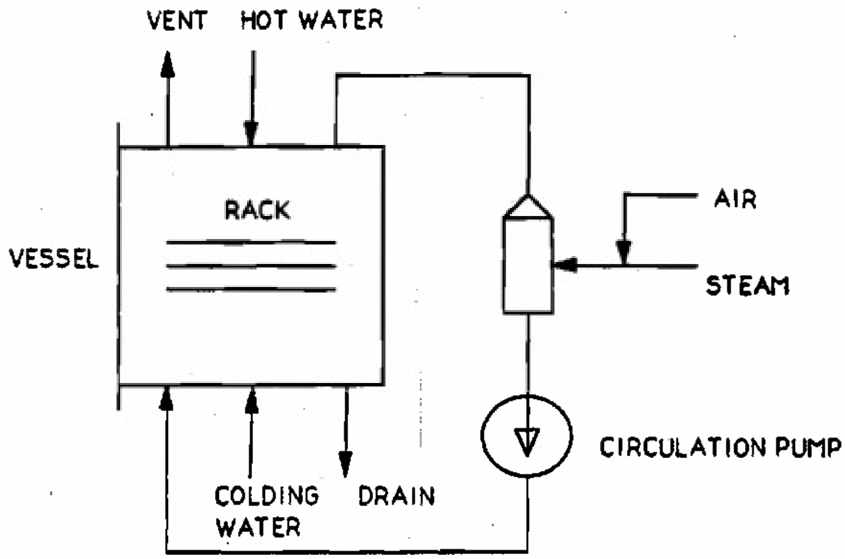

Fig. 2 Experimental tray retort configuration for processing with heated water

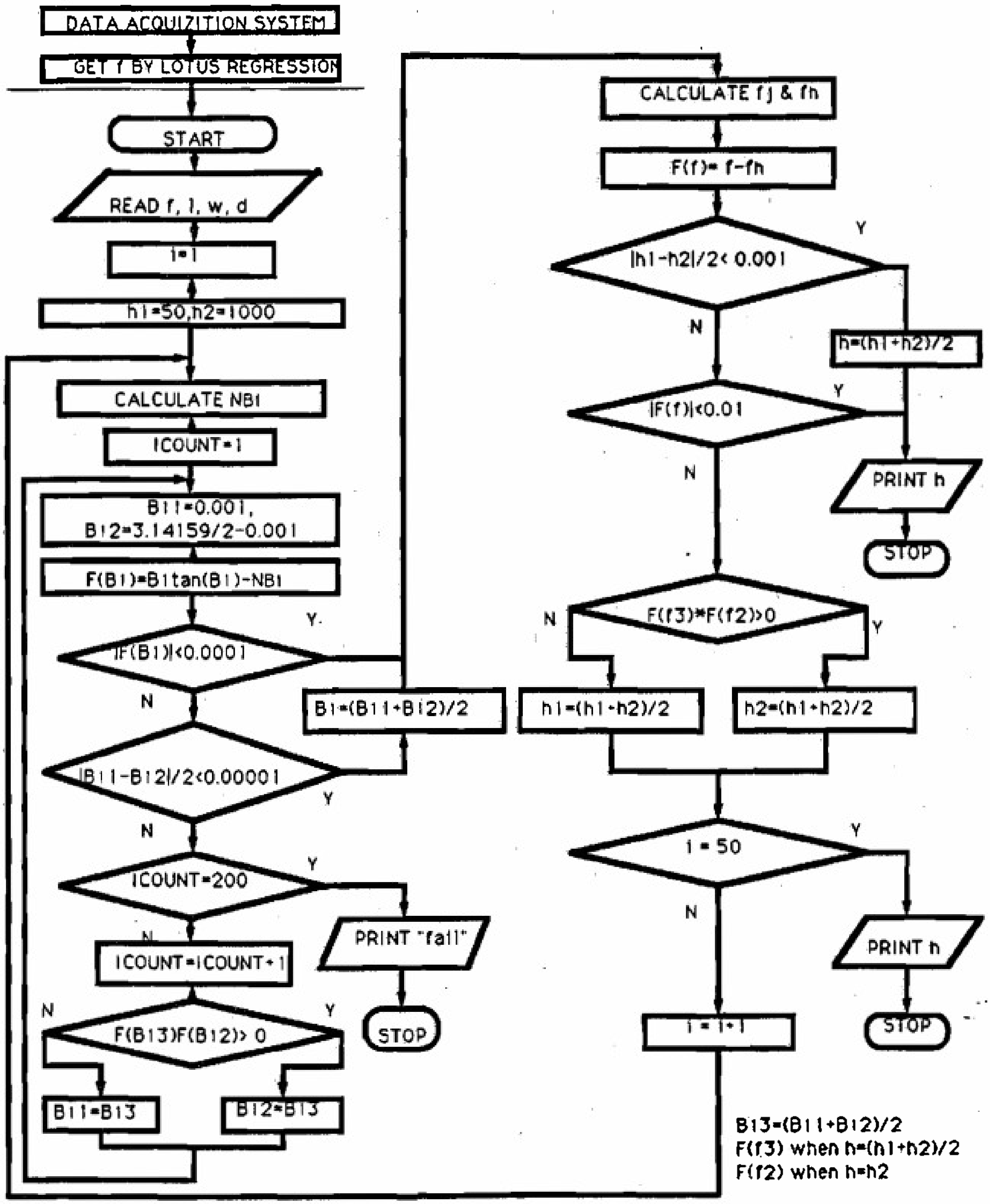

Fig.3 FLOW CHART OF OPTIMIZATION PROGRAM

190

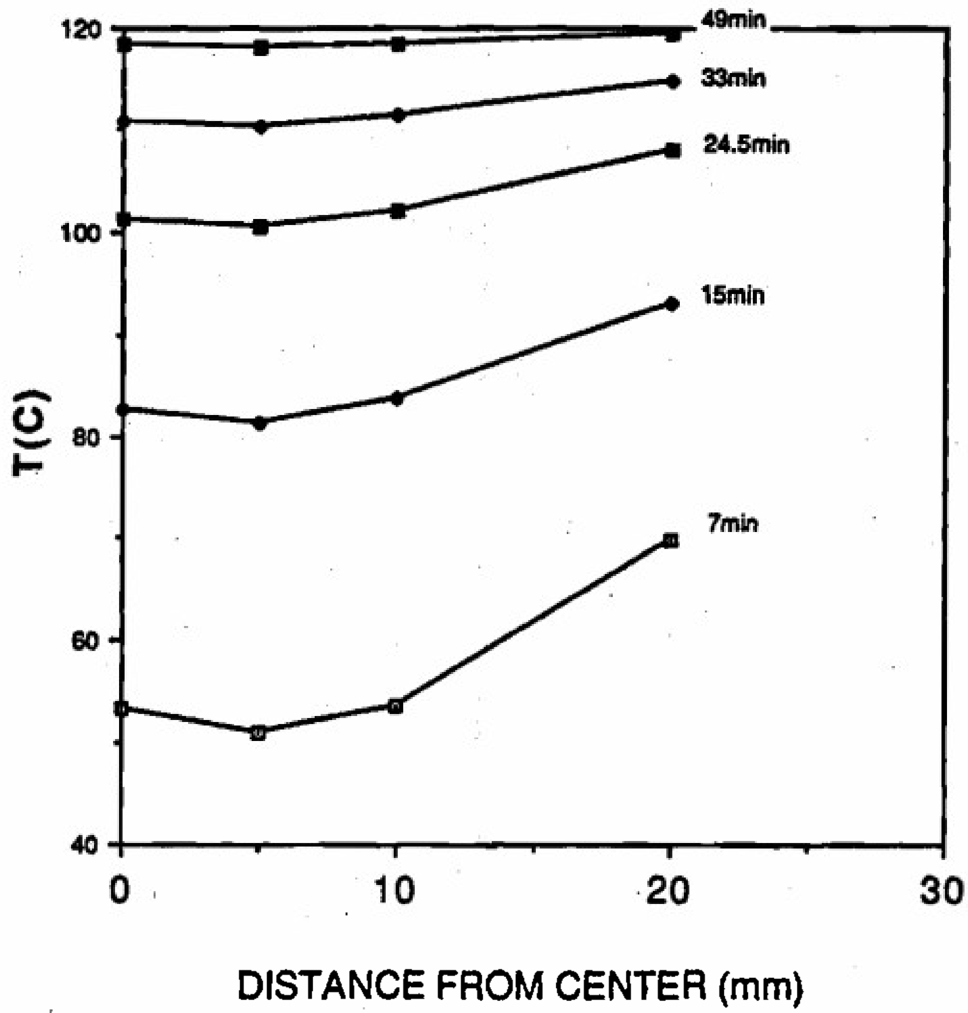

FIG.4 COMPARTMENT 1 TEMP PROFILE

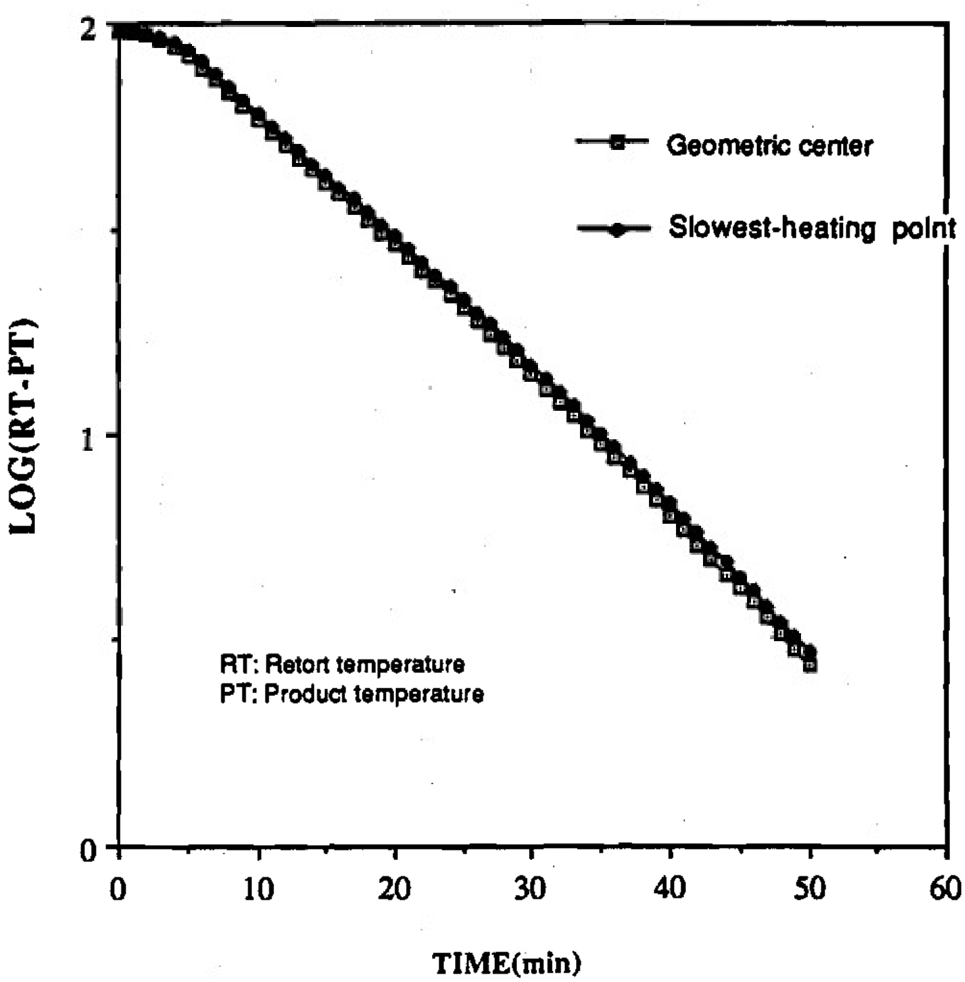

Fig.5 TYPICAL HEATING CURVES FOR COMPARTMENT (GEOMETRIC CENTERS VERSUS SLOWEST-HEATING POINT)

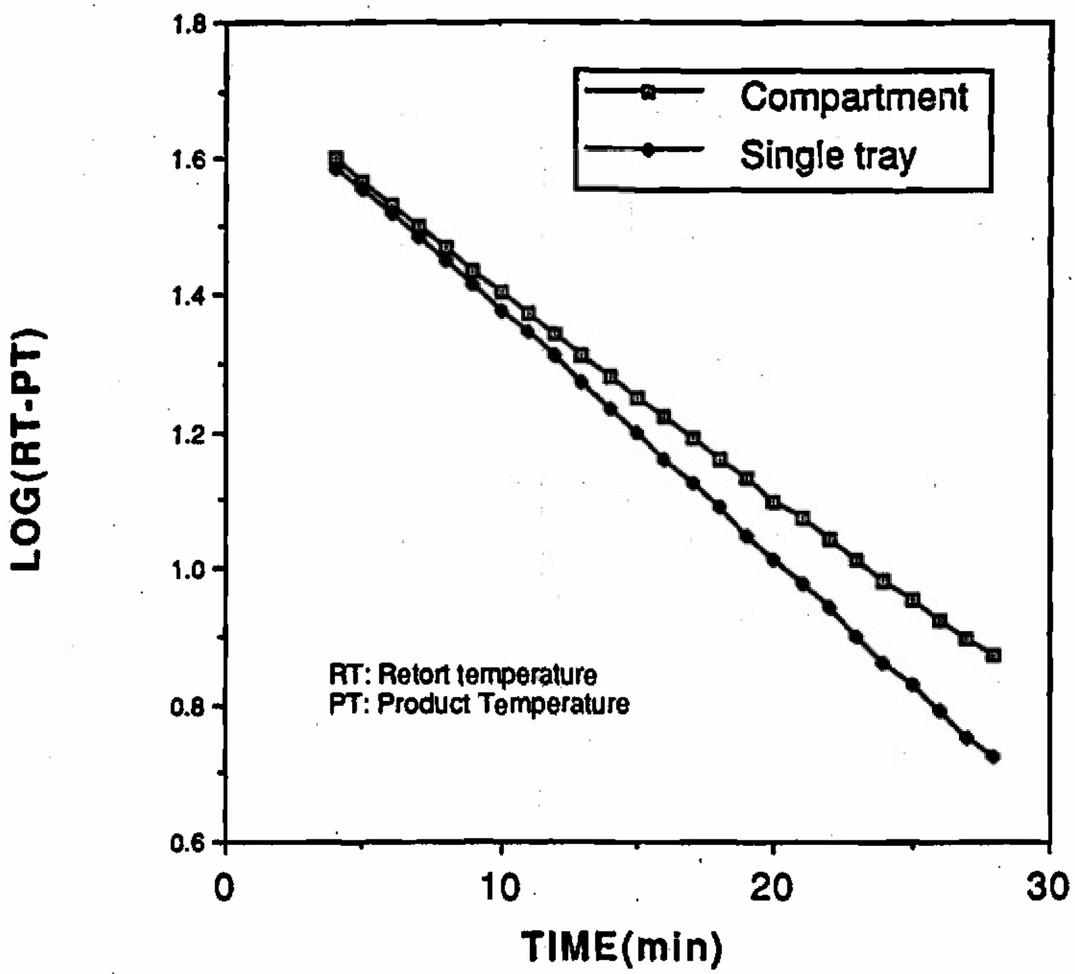

Fig.6 TYPICAL HEATING CURVES FOR COMPARTMENT TRAY VERSUS SINGLE TRAY

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